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GROUNDWATER AND SURFACE-WATER INTERACTIONS ALONG
LOWER MEDANO CREEK, GREAT SAND DUNES
NATIONAL MONUMENT, COLORADO

by

Gregg L. Hadlock

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Geology

Approved:

UTAH STATE UNIVERSITY
Logan, Utah

1995

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Gregg L. Hadlock

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ABSTRACT

Groundwater and Surface-Water Interactions along
Lower Medano Creek, Great Sand Dunes
National Monument, Colorado

by

Gregg L. Hadlock, Master of Science
Utah State University, 1995

Major Professor: Dr. Thomas E. Lachmar
Department: Geology

The objectives of this investigation are as follows:

- 1) review the existing hydrogeologic data for the San Luis Valley, the Great Sand Dunes Monument, and Medano Creek;
- 2) review the surface-water data that have been collected on Medano Creek;
- 3) collect or review previously collected water-level data obtained in the area of lower Medano Creek and correlate them with the surface-water data;
- 4) conduct constant-head permeameter tests on sand samples collected near the ground surface along lower Medano Creek;
- 5) produce a conceptual model of lower Medano Creek; and
- 6) produce a numerical model of lower Medano Creek that will predict the effect that a lowering of the regional water table could have on the terminus of flow of Medano Creek.

The complex hydrogeologic conditions under lower Medano Creek have been approximated with three homogeneous and anisotropic layers. A complex system of confining layers is represented by a single low-hydraulic-conductivity layer in the middle.

Numerical-modeling results suggest that the location of the terminus of flow in Medano Creek will recede significantly in response to a lowering of the regional water table, possibly by as much as 21,000 feet (6,400 meters) if the regional water table is lowered 150 feet (46 meters). These results indicate the qualitative effect that a lowering of the regional water table would have on lower Medano Creek, but they cannot be considered to be precise quantitative predictions. The results should be regarded with caution due to the paucity of data available.

(88 pages)

CHAPTER I

INTRODUCTION

Statement of the Problem

Proposed groundwater withdrawals in the adjacent Baca Grande property north of the Great Sand Dunes National Monument, San Luis Valley, Colorado, may lower the regional water table in the monument. Regional water-table declines of 150 feet (46 meters) are projected if the proposed groundwater withdrawals take place (McCalpin, 1991a). Because of this possibility, the National Park Service initiated a study to determine the effects that a lowered regional water table would have on surface-water flow in the monument.

Due to its rare surging-flow phenomenon (Bean, 1977; Schumm et. al., 1982), Medano Creek is a primary visitor attraction in the Great Sand Dunes National Monument. The National Park Service is concerned with the effect that a lowered regional water table would have on the surging flow in Medano Creek. This investigation is part of a larger research project to: 1) characterize the surface flow of Medano Creek; 2) characterize the relationship between surface flow in Medano Creek and the groundwater system; and 3) evaluate the potential adverse effects that a lowered regional water table might have on the surging flow of Medano Creek.

Purpose and Objectives

The primary purpose of this investigation is to develop a numerical model that will help predict the effects that a lowered regional water table could have on the portion of Medano Creek downstream of the Castle Creek flume. The objectives of this investigation are as follows: 1) review the existing hydrogeologic data for the San Luis Valley, the Great Sand Dunes National Monument, and Medano Creek; 2) review the surface-water data that have been collected on Medano Creek as part of the larger investigation; 3) collect or review previously collected water-level data obtained in the area of lower Medano Creek and correlate them with the surface-water data; 4) conduct constant-head permeameter tests on sand samples collected near the ground surface of lower Medano Creek; 5) produce a conceptual model of lower Medano Creek; and 6) produce a numerical model of Medano Creek that will predict the effect that a lowering of the regional water table could have on the surface flow of Medano Creek.

Location

The Great Sand Dunes National Monument is on the eastern edge of the San Luis Valley northeast of Alamosa, in south-central Colorado (Figure 1). The area studied in detail for this project is lower Medano Creek. The area

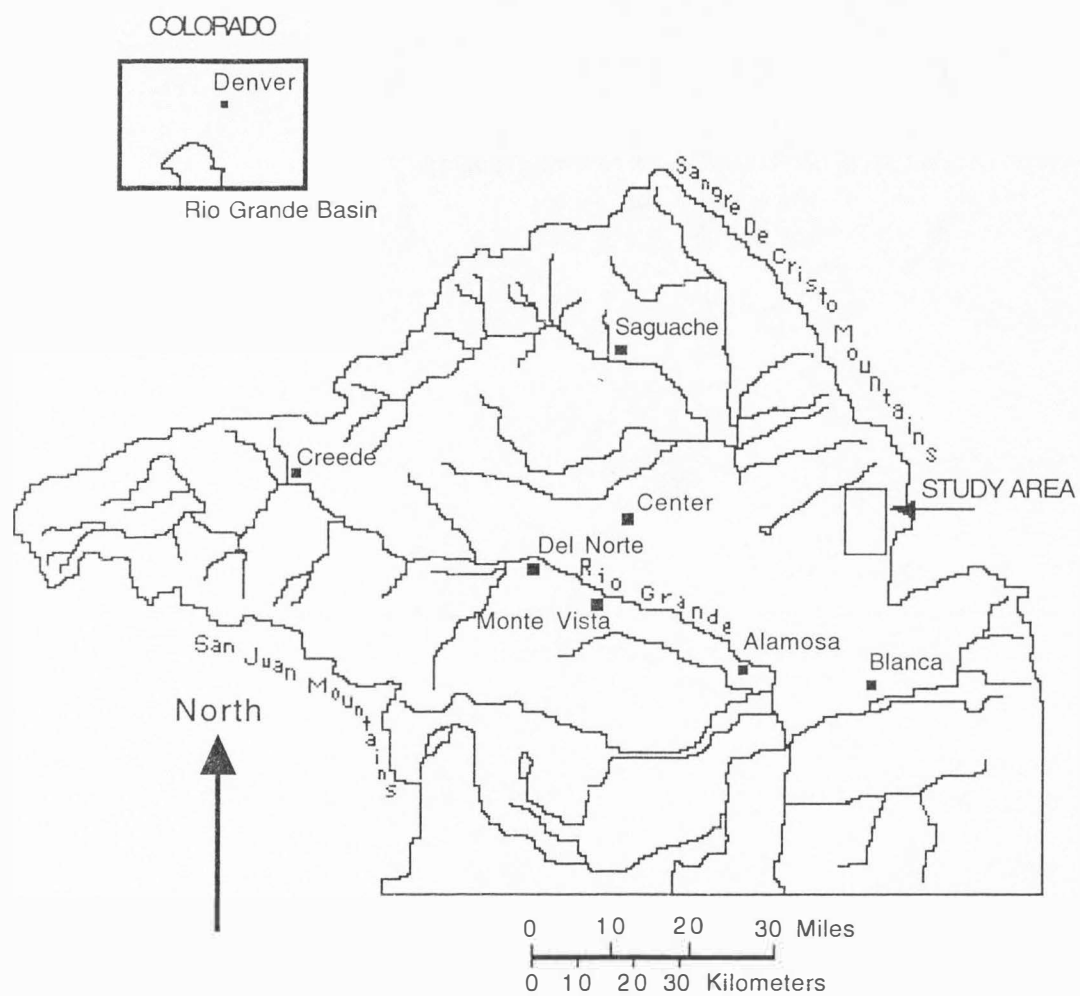


Fig. 1. Location map of the study area.

where the numerical model was constructed begins where Medano Creek's stream bed changes from a single channel covered mainly by cobbles to a braided channel covered almost entirely by sand. This is approximately 1,000 feet (305 meters) downstream from the Castle Creek flume. The model ends at the location of the approximate average maximum annual terminus of flow. Figure 2 shows important features in the study area.

Previous Investigations

Hydrogeology

The first geologic investigation of the San Luis Valley was by Ingersoll (1875), who studied the geomorphology of the area. Endlich (1876) studied the geomorphology, stratigraphy, mineralogy, and hydrogeology of the area. Additional studies on the hydrogeology of the area include Siebenthal (1910), Lakes (1910), Headden (1919), Powell (1958), Emery (1971, 1982), Emery et al. (1972), Huntley (1976, 1979), Qazi (1983), Hearne and Dewey (1988), and Leonard and Watts (1989). The stratigraphy and structure of the San Luis Valley have been investigated by Upson (1938, 1939), Huntley (1979), and McCalpin (1983). The Great Sand Dunes National Monument has been studied by Meri (1960, 1973), Johnson (1968), and Andrews (1978).

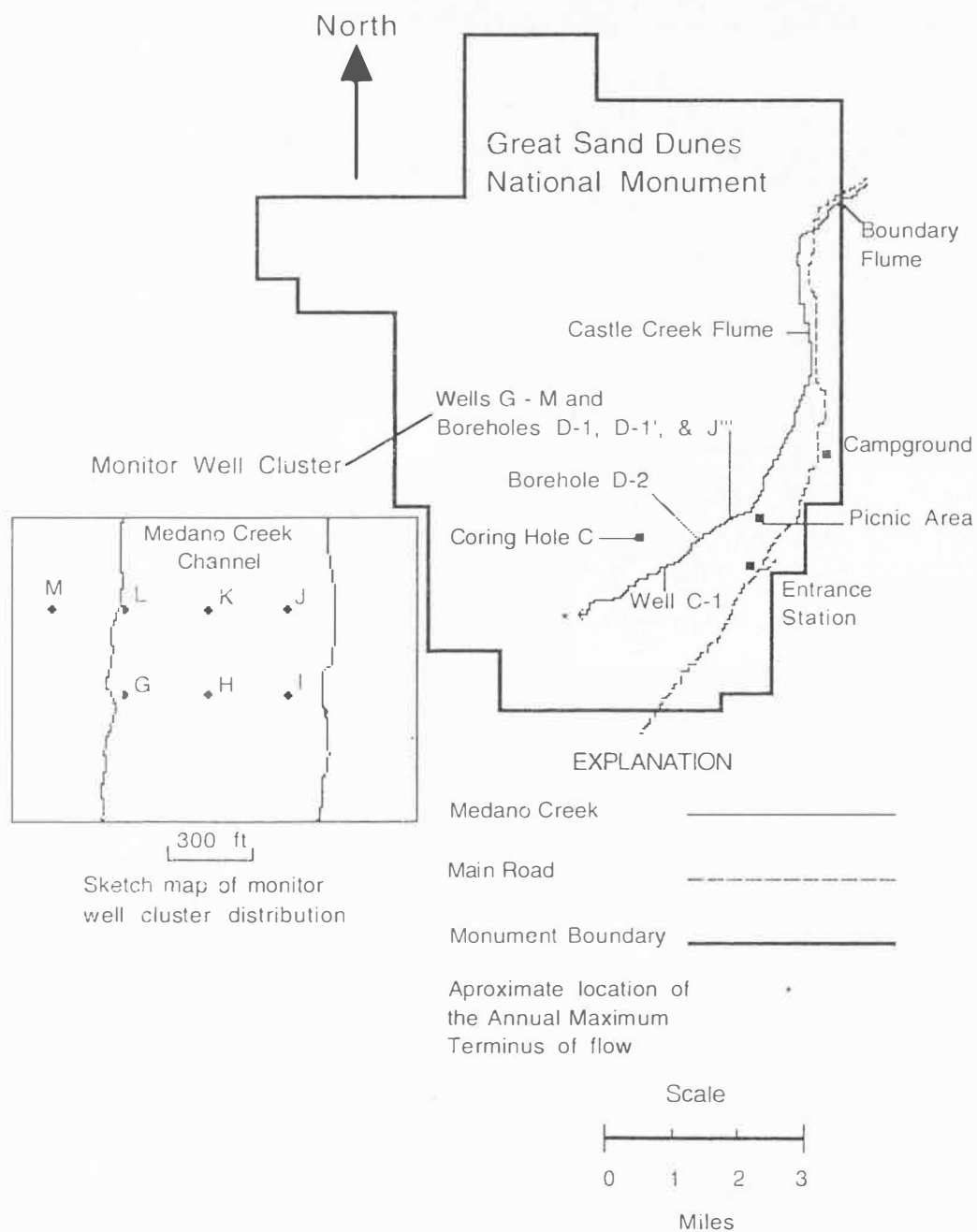


Fig. 2. Detailed map of the study area.

The hydrogeology of the Great Sand Dunes National Monument has not been studied in detail. However, a great deal of geologic work has been done within the monument during the last few years. While none of this work conclusively characterizes the hydrogeology of Medano Creek, it is useful in producing a reasonably accurate conceptual model. The hydrogeology of the San Luis Valley is also useful in characterizing the hydrogeology of Medano Creek. Much of the following information is summarized from McCalpin (1991a), and some of the more pertinent studies of the San Luis Valley are discussed also.

The Great Sand Dunes National Monument lies along the margin of a fault-bounded basin. Huntley (1976) and Emery (1971) both described the San Luis Valley as a typical fault-bounded basin with large infiltration rates along the margins of the valley. This pattern of infiltration is due to the facies relationships normally found in such basins. Thick, low-hydraulic-conductivity, clayey layers are deposited in the centers of such basins. The clayey layers thin and become discontinuous toward the boundaries of such basins. The thinning of the clayey layers allows increased infiltration rates. In addition, alluvial fans located at the boundaries of a fault-bounded basin are normally porous and have high hydraulic-conductivity values (Williams, 1962; Davis and DeWeist, 1966).

Large infiltration rates within the Great Sand Dunes National Monument result from a cover of permeable eolian sand and the lack of continuous clayey layers. This configuration causes the flow of Medano Creek and Mosca Creek to terminate within the boundaries of the monument.

A regional report on the Alamosa Basin (Hearne and Dewey, 1988, pp. 42-46) described the region's hydrogeology:

The Alamosa Basin is bounded by the Sangre de Cristo Mountains on the east, the San Juan Mountains on the west, and the San Luis Hills on the south. The Rio Grande flows into the Alamosa Basin from the San Juan Mountains and flows from the valley through a gap in the San Luis Hills. The Alamosa Basin contains several thousand feet of interbedded gravel, sand, silt, clay, and volcanic rocks that form a leaky artesian aquifer system. A common description of the aquifer system is based on the division of the aquifer system into an "unconfined aquifer" and a "confined aquifer" separated by either a clay series or unfractured volcanic rocks. These subdivisions are useful in describing general features of the aquifer system, but they need to be used with caution. The conceptual system accepted here is not of two aquifers separated by an impermeable confining bed but rather of complexly interlayered aquifers and leaky confining beds, each of limited areal extent and variable hydraulic properties. The resulting complex is a heterogeneous, anisotropic aquifer system.

Most deep wells in the Alamosa Basin probably are completed in more than one aquifer of the system. Analysis of water levels from such wells requires supportive data that may or may not be available. Hydraulic head in the well depends on depth of the well, aquifers to which the well is completed, and the hydraulic head and hydraulic conductivity of each aquifer. Wells completed to more than one aquifer may be conduits for flow between aquifers either with or without flow at the surface. Hydraulic head in the well is a composite of hydraulic heads in the aquifers with which the well is in hydraulic connection. For such an aquifer system, hydraulic head in a well

completed to more than one stratum may provide little or no information about hydraulic head in an individual stratum. Potentiometric surface is a valid concept only if the particular stratum in the aquifer system is specified; the water table is the potentiometric surface in the uppermost saturated strata of the aquifer system. Surfaces representing water levels in wells of variable depths do not constitute a potentiometric surface.

Geophysics

In June of 1991, the Geophysics Department of the Colorado School of Mines conducted a field camp in the Great Sand Dunes National Monument at the invitation of the National Park Service. The Park Service hoped to gain information on the subsurface geologic structure of the Medano Creek area to aid their ongoing hydrogeologic investigation. However, the primary purpose of the field camp was to educate geophysics students. The following information is taken from the final report of the Colorado School of Mines to the National Park Service (Powers, 1992).

During the field camp, the following geophysical methods were used to survey the Medano Creek area:

- 1) gravity, 2) magnetics, 3) DC electrical,
- 4) electromagnetic, 5) refraction seismic, and
- 6) reflection seismic. The majority of the surveys conducted by the School of Mines were conducted in the area of upper Medano Creek (between the Castle Creek flume and the monument boundary) and in the canyons east of upper

Medano Creek. These surveys all attempted to locate the surface water table and the bedrock contact in the areas studied. In the upper Medano Creek area and the canyons east of upper Medano Creek, the bedrock contact was generally interpreted to be deepening toward the west, whereas the water table drops westward from a depth of 20 feet (6 meters) to a depth of approximately 50 feet (15 meters) and remains at that depth. In the east the drop in the water table appears to correspond to the deepening of the bedrock. The water table and the bedrock diverge to the west.

A class project, separate from the 1991 field camp, was undertaken by personnel of the Colorado School of Mines in November of 1991. A refraction seismic line was acquired near wells G-M. Data for the refraction line were obtained with a hammer source and with an explosive source. The data obtained with the hammer source were for the velocity interfaces at shallow depths. Unfortunately, the quality for the shallow seismic refraction data was not good. The poor quality of these data did not allow conclusive results. The bedrock contact underlying the creek was not found in the lower Medano Creek area. The seismic data suggest that the sand underlying lower Medano Creek is not completely saturated or that it is only saturated in unconnected pockets. The seismic data also indicate that

less permeable saturated alluvial material exists below a depth of 100 feet (30 meters). In the lower Medano Creek area, the surface water table appears to be controlled by the flow of Medano Creek, not by the depth to the underlying bedrock (Powers, 1992).

On February 14, 1991, personnel of the U.S. Geological Survey conducted a sled-mounted, ground-penetrating radar survey in the vicinity of wells G-M to a depth of approximately 100 feet (30 meters). This survey showed an undulating "hard layer" at a depth of 10 to 14 feet (3 to 4 meters) under Medano Creek (Oelhoeft, oral communication, 1994). This layer was found at a slightly greater depth in borehole J''' during drilling in the area. This layer was not found in borehole D-2 downstream from borehole J'''. The survey also showed other discontinuous layers of sand and gravel at various depths.

On December 13 and 14, 1991, an electrical-resistivity sounding was done near wells G-M by J.P. McCalpin and M. Nelson. The survey was done to gain information on the hydrogeology of the area. The results of this survey were inconclusive (McCalpin, 1992b).

CHAPTER II

DATA COLLECTION

Geophysics

In July and September of 1992, an electrical-resistivity survey was conducted in the area of wells G-M with a Bison 2350 electrical-resistivity instrument. At the time of this survey, data from previous geophysical work done in the lower Medano Creek area were not available, and very little was known about the hydrostratigraphy of lower Medano Creek at depths of more than 20 feet (6 meters). It was hoped that the survey would locate any low-hydraulic-conductivity layers underlying Medano Creek and provide information on water levels and the moisture content of the sand underlying the creek.

The results of the survey were inconclusive. Problems were encountered in obtaining reproducible and reasonable results. The electrical-resistivity method is limited to simple structural configurations, and near-surface resistivity variations can mask the effects of deeper variations (Keary and Brooks, 1984). Due to these limitations, electrical resistivity is not a particularly good geophysical method to use in this area.

A seismic survey was also conducted in July and September of 1992. This survey was done with a Geometronix

12-channel signal enhancement engineering seismograph. No information was obtained during this survey. The coupling of the geophones with the loose sand was insufficient for the geophones to pick up the vibrations sent out by the hammer. The geophones only recorded background noise. In future surveys, better results may be obtained by burying the geophones to increase their coupling with the ground, and by using a filter to block out some of the background noise (Parasnis, 1979).

Surface Water

It is necessary to collect certain surface-water data in order to understand the groundwater and surface-water interactions along lower Medano Creek. This surface-water information is also necessary to constrain certain input parameters required for numerical modeling. The following information was obtained from field investigations and from the available literature.

Terminus of Flow

The position of the terminus of flow of lower Medano Creek was measured by Park Service personnel between about noon and 1:00 P.M. each day. The measurements were taken from March 19 to April 17, 1993, by pacing downstream from a known point. One additional measurement was taken on April 26, 1993. A graph of the position of the flow

terminus and the discharge of Medano Creek at the Boundary flume through time shows that the two plots are reasonably parallel (Figure 3).

Infiltration Rates

Stream flow along Medano Creek has been measured with Parshall flumes installed at two locations. The flumes have throat sections 3 feet wide. The flumes' other dimensions are dictated by the dimensions of calibrated flumes tested by the U.S. Bureau of Reclamation (Bureau of Reclamation, 1984). The flumes were installed on June 28, 1991 (McCalpin, 1991b). The upstream flume (Boundary flume) is near the boundary of the monument in order to record the stream flow entering the monument. The downstream flume (Castle Creek flume) is located in the last channel narrow enough to accommodate a flume. Downstream of the Castle Creek flume, Medano Creek's stream bed changes to sand and the stream spreads out.

Prior to September 15, 1991, a Druck pressure transducer was used to measure water depths in the flumes. The data were recorded with an Omnidata Data Pod II data logger. After September 15, 1991, the measurements were made using a float connected to an Omnidata DP-115 data logger (McCalpin, 1991b).

Stream discharge data from the Boundary flume were collected from June 28, 1991, to November 7, 1992; and from

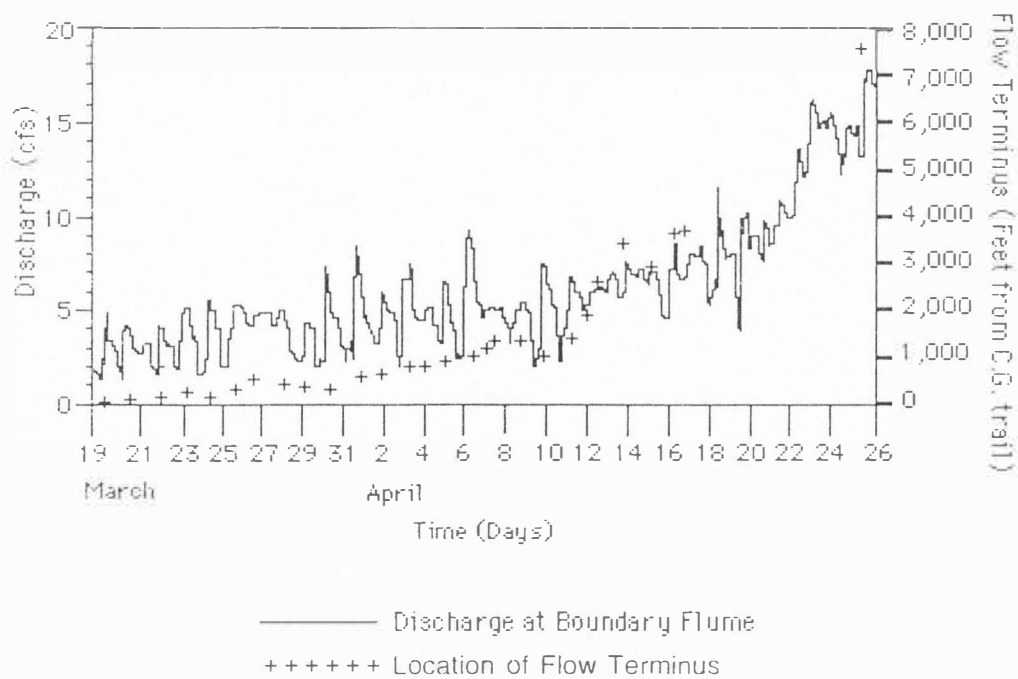
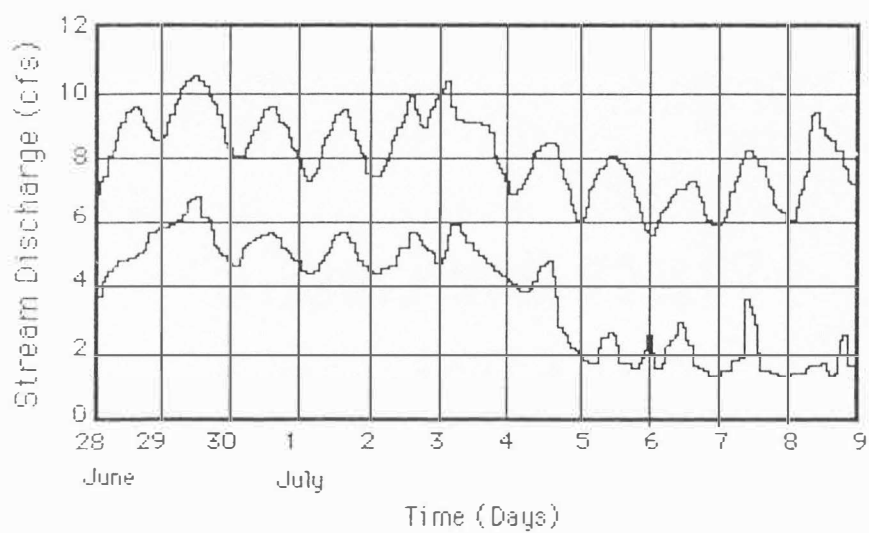


Fig. 3. Discharge and position of flow terminus versus time.

March 7, 1993, to May 25, 1993. Discharge data from the Castle Creek flume are available from June 28, 1991, to April 9, 1992, with some brief periods of missing data. Discharge data are represented graphically in Figure 4. These measurements were verified by periodic visual observation of the water depth in the flumes by monument personnel (McCalpin, 1993).

McCalpin and others measured the stream losses in lower Medano Creek from June 20 through June 24, 1991 (McCalpin, 1991b and 1992a). The stream-bed losses were estimated by taking discharge measurements at two different locations on lower Medano Creek and calculating the loss in discharge by subtracting the downstream discharge measurement from the upstream discharge measurement. Current velocities were measured at 60 percent of channel depth with a pygmy current meter at intervals of 2 feet across the channel. Channel width was measured with a steel tape. Channel depth was measured with the wading rod for the current meter. Discharge was then calculated as a summation of the products of the velocity measurement multiplied by the cross-sectional area for each lateral interval of 2 feet. Because discharge on lower Medano Creek fluctuates diurnally, measurements taken at different times cannot necessarily be used to estimate stream losses. This problem was overcome from an upstream measurement, then a



Boundary Flume Measurements on the Top

Castle Creek Flume Measurements on the Bottom

Fig. 4. Castle Creek flume and Boundary flume discharge graph.

downstream measurement and then another upstream measurement, and then averaging the two upstream measurements to obtain the approximate upstream discharge at the time of the downstream measurement. From this technique, an average stream loss of 3.7 cubic feet per second (ft^3/sec) ($0.1 \text{ m}^3/\text{sec}$) was estimated from several sets of upstream and downstream measurements obtained during a relatively high-flow period between June 20 and June 24, 1991. The distance between the upstream and downstream measurement points was about one mile (1.6 kilometers) (McCalpin, 1991a and 1992b).

Measurements taken at the Castle Creek flume show a maximum discharge of $25 \text{ ft}^3/\text{sec}$ ($0.71 \text{ m}^3/\text{sec}$) from June 12, 1992, to June 14, 1992. The maximum values of discharge in 1991 and 1993 are not available. In the data used to calculate the infiltration rate of lower Medano Creek, a discharge of $25 \text{ ft}^3/\text{sec}$ ($0.71 \text{ m}^3/\text{sec}$) is lost in 32,000 feet (9,750 meters). This would correspond to a stream loss of $4.1 \text{ ft}^3/\text{sec}$ per mile ($0.073 \text{ m}^3/\text{sec}$ per kilometer). This compares favorably with the value of $3.7 \text{ ft}^3/\text{sec}$ per mile measured by McCalpin and others (McCalpin, 1991b and 1992a). Because both of these stream-loss values are estimations, the agreement between them is very good.

The surface area of lower Medano Creek has been estimated from aerial photographs obtained from Park

Service personnel. The photographs were taken in 1990 (the exact date is unknown). The location of the terminus of flow of Medano Creek shown in the photographs indicates, and Park Service personnel confirm, that the photographs were taken near the time when the normal spring-time maximum discharge usually occurs. The photographs were used because they appeared to coincide roughly with the time of year that the discharge of $25 \text{ ft}^3/\text{sec}$ was measured at the Castle Creek flume. The areal extent of Medano Creek shown in these aerial photographs has been used to calculate the approximate surface area of the creek at maximum discharge. A tracing was made of the wetted perimeter of lower Medano Creek. The area of the stream was then calculated with a compensating polar planimeter and based on estimation of the scale of the photographs by comparison of known points on the photographs to known points on a map of the monument. The area of Medano Creek calculated was $11.2 * 10^6 \text{ ft}^2$ ($10.4 * 10^5 \text{ m}^2$).

The evapotranspiration rate for Medano Creek was estimated from literature on the Alamosa Basin. Hearne and Dewey (1988, p. 46) estimated the evapotranspiration rate along stream channels and in riparian areas to be 4.5 ft/yr (1.4 m/yr).

The discharge of lower Medano Creek, the area of lower Medano Creek, and the estimated evapotranspiration were

then used to calculate the infiltration rate of Medano Creek. The infiltration rate was calculated with the following equation:

$$\text{Infiltration Rate} = (\text{Discharge} / \text{Area}) - \text{Evapotranspiration}$$

The infiltration rate of lower Medano Creek calculated in this manner, by substituting 25 ft³/sec (0.71 m³/sec), which after unit conversion equals 7.884 * 10⁸ ft³/yr (2.234 * 10⁷ m³/yr), for discharge, 11.2 * 10⁶ ft² (10.4 * 10⁵ m²) for area, and 4.5 ft/yr (1.4 m/yr) for evapotranspiration, is 66 ft/yr (20 m/yr). The discharge value used in calculating the infiltration rate of lower Medano Creek represents an annual peak discharge value. In order to produce results, the numerical model must be run until steady-state conditions are reached, which requires a constant discharge value. A peak discharge value was used because the Park Service is concerned with the effect that a lowered regional water table might have on the surging flow in Medano Creek in the vicinity of the picnic area. The picnic area is inundated by the creek only when the discharge is relatively high during the late spring and early summer. Thus, using a peak-discharge value provides a "worst-case" prediction for the effect that a lowered regional water table might have on the surface flow of lower Medano Creek.

It should be noted that the actual yearly discharge and infiltration-rate values of lower Medano Creek are much less than the values for discharge and infiltration calculated above.

Groundwater

The following groundwater and hydrostratigraphic information was obtained during field investigations in the lower Medano Creek area. This information is vital to understanding the groundwater and surface-water interactions along lower Medano Creek. The groundwater and hydrostratigraphic information is also needed to constrain certain input parameters required for numerical modeling.

Monitor Wells

A cluster of six monitor wells was completed in the lower Medano Creek area by National Park Service personnel in December 1990. The cluster of monitor wells is in the Medano Creek stream bed approximately 17,000 feet (5,200 meters) downstream from the Castle Creek flume. The monitor wells form two roughly east-west lines 300 feet (91 meters) apart. The wells in each line are also 300 feet (91 meters) apart. The southern line of monitor wells contains wells G, H, and I, with well G on the west and well I on the east. The northern line of monitoring wells contains wells J, K, and L, with well J on the east and well L on the west

(Figure 2). All of the wells are completed with 2-inch PVC casing.

On August 25, 1991, well M was added to the cluster of monitor wells. Well M is located 250 feet (76 meters) west of monitor well L. It was drilled by National Park Service personnel using a manually powered auger, and was completed with 2-inch PVC casing.

From April 7 through 8, 1992, three monitor wells were drilled by J.P. McCalpin and L.C.A. Jones in the lower Medano Creek area. Two of the wells, well J' and well J'', were drilled adjacent to monitor well J. The third well, C-1, was drilled approximately 9,800 feet (3,000 meters) downstream from the cluster of monitor wells. The wells were drilled with a Giddings solid-stem auger rig. The wells were completed with 1 5/8-inch steel pipe threaded onto a 1-foot-long sand point with a No. 8 screen on the end. The stratigraphy of each well was the same: 6 to 12 feet (2 to 4 meters) of clean medium sand, underlain by 5 to 8 feet (1.5 to 2.5 meters) of sandy gravel, underlain by a "hard" layer at least 4 feet (1 meter) thick. No sample of the "hard" layer was retrieved (McCalpin, 1992a).

Water Levels

Groundwater levels have been measured manually with an electric probe and/or a steel tape in all of the monitor wells. In addition, Druck pressure transducers connected to

Omnidata DataPod II data loggers were installed in wells J and L on September 28, 1991, and in well C-1 on April 10, 1992. The transducers were calibrated to known water levels, which were measured with a cloth tape with an electrosensitive probe on the end. The water-level data for monitor wells L, J, and C-1 are shown in Figures 5, 6, and 7, respectively.

The water levels in well J were monitored from September 28, 1991, to April 10, 1992, when well J, which is located in the lowest part of the floodplain, became submerged beneath the creek and filled with sand. Well J was also monitored from March 19 to May 10, 1993. Well L has a longer continuous record of water levels, as it was monitored nearly continuously from September 28, 1991, to January 2, 1993.

Water-level fluctuations in monitor well L for the period of record can be divided into four segments (Figure 5): 1) a period of slow water-level decline from September 28, 1991, to March 29, 1992; 2) a period of slow and then rapid water-level rise from March 29 to May 28, 1992; 3) a period of constant water level from May 28 to August 25, 1992; and 4) a period of rapid and then slow water-level decline from August 25, 1992, to January 2, 1993.

From September 28, 1991, to March 29, 1992, the water level in well L fell slowly and steadily. The water level

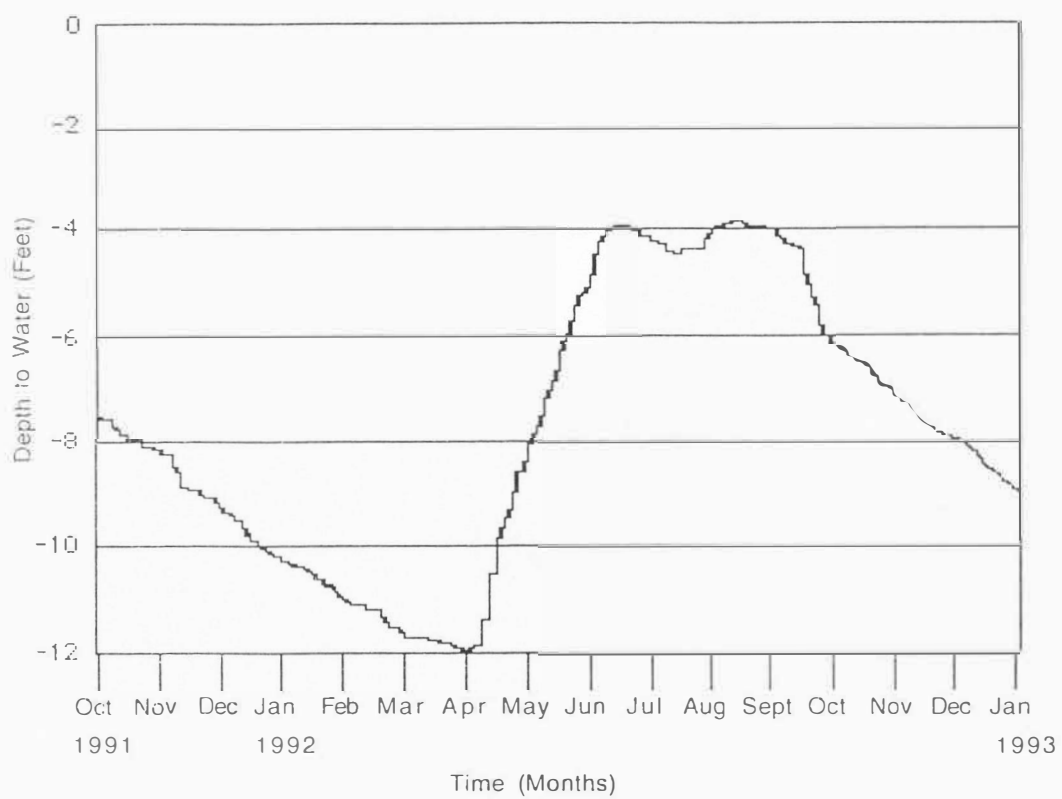


Fig. 5. Depth to water, monitor well L.

in well L fell about 4 feet (1.2 meters) in 6 months.

From March 29 to May 28, 1992, there was a slow and then rapid water-level rise in well L. The terminus of flow of lower Medano Creek did not arrive at the monitor-well cluster until April 8, 1992. Rapid rise of the water level in well L did not begin until roughly one day after the flow terminus of Medano Creek had passed. This suggests that there is a short lag time after the advance of the flow terminus during which the shallow groundwater system is filled up with infiltration from Medano Creek.

From May 28 to August 25, 1992, the water level remained rather constant in well L. During this time, the Boundary-flume records indicate that discharge declined from 35 ft³/sec (0.99 m³/sec) to 5 ft³/sec (0.14 m³/sec). The water level in well L stood at about 4 feet (1.2 meters) below the top of casing throughout this period, with two minor fluctuations: 1) a period of rapid water-level decline from July 8 to July 16, 1992; and 2) a period of rapid and then slow water-level rise from July 16 to July 23, 1992. From July 8 to July 16, the discharge at the Boundary flume declined only slightly, from 9 ft³/sec (0.25 m³/sec) to 7 ft³/sec (0.20 m³/sec). This rapid decline probably indicates that the flow terminus of lower Medano Creek retreated to just upstream of the monitor-well cluster during this week. The water level rose abruptly 0.5

feet (0.15 meter) on July 16 and continued to rise another 0.2 to 0.3 foot (0.06 to 0.09 meter) during the following week. The abrupt water-level rise coincided with a sudden increase in discharge of about 5 ft³/sec (0.14 m³/sec) at the Boundary flume. The increased discharge at the Boundary flume was due to the return of water previously diverted from the creek at Medano Pass for irrigation. If this renewed flow had not occurred, the water level probably would have continued the downward trend that began on July 8. The additional surface flow in the creek probably readvanced the flow terminus of lower Medano Creek to downstream of the monitor wells.

From August 25, 1992, to January 2, 1993, there was a period of rapid and then slow water-level decline in well L. During the first 2 weeks of this period, the water level declined 2 feet (0.6 meter). This decline is very rapid, and must represent the final seasonal retreat of the flow terminus to upstream of the monitor wells. During the remainder of this period, the water levels declined slowly, from about 4 feet to 8.5 feet (1.2 to 2.6 meters) below the top of the casing. This slow water-level decline is essentially identical to the slow water-level decline observed from September 28, 1991 to March 29, 1992.

Water levels in monitor well J were recorded throughout the spring-runoff period from March 19 to May

10, 1993 (Figure 6). These data show a constant water level at about 4.7 feet (1.4 meters) below the top of the casing until April 21. From April 21 to April 23, the water level rose slowly, and then late on April 23 the rate of water-level rise increased greatly. The water level rose 3.7 feet (1.1 meters) in the next 4 days before coming to a new stable position at 1 foot (0.3 meter) below the top of the casing. The rapid rise in the water level is attributed to the arrival of the flow terminus of lower Medano Creek. This supposition is supported by the similar reaction of well L to the arrival of the flow terminus in the spring of 1992. However, no observations of the flow-terminus position were made between April 17 and April 26, so the supposition cannot be strictly verified. By linear interpolation, the date of arrival of the flow terminus at monitor well J can be estimated to be about mid-day on April 22 (Figure 3). April 22 is roughly midway through the early period of slow water-level rise. If the interpolation is accurate, then the water level in well J did not begin to rise rapidly until about a day and a half after the flow terminus reached the well. This is slightly longer than the roughly one-day lag time observed in April of 1992 at well L. The reason for the slight discrepancy is probably a mis-estimation of the true arrival time of the flow terminus.

Borehole C-1 was instrumented with a pressure

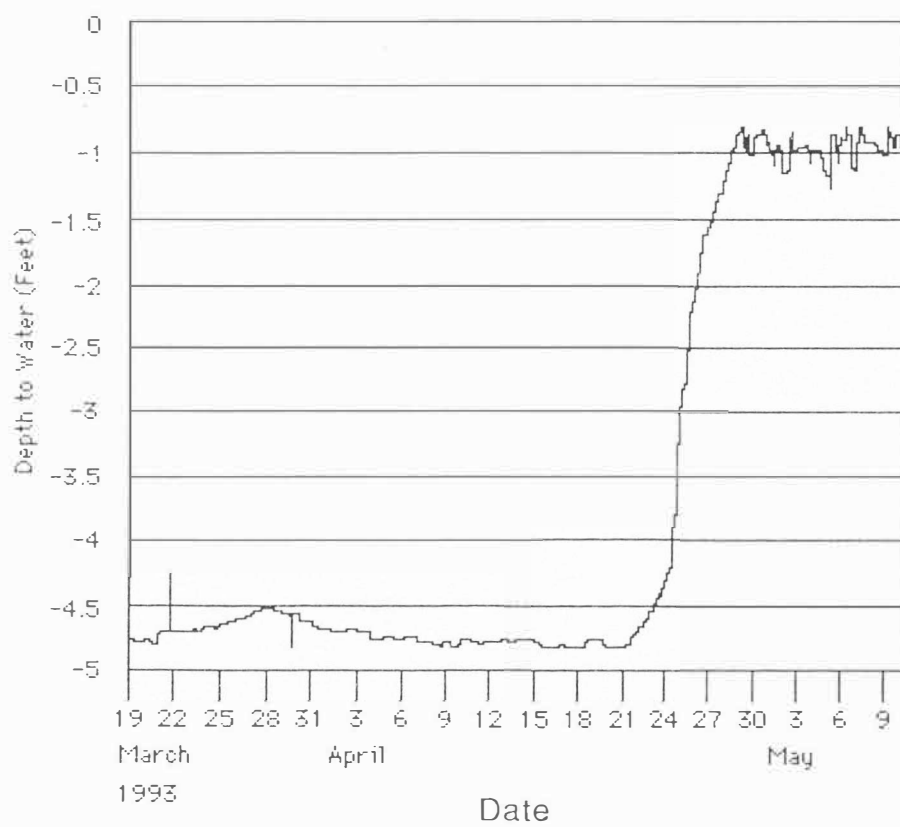


Fig. 6. Depth to water, monitor well J.

transducer and data logger to observe how fast the shallow aquifer beneath lower Medano Creek would fill upon the approach of the flow terminus. The water level remained at 14.9 feet (4.5 meters) below the ground surface, which is the very bottom of the borehole, from April 11 to April 18, 1992 (Figure 7). On April 18, the water level began to rise rapidly. In approximately 24 hours, the water level was at the surface. The extremely rapid rise in the water level implies that water infiltrating from the stream bed is being impeded in its downward movement by the hard layer encountered at the bottom of borehole C-1.

Based on this limited information, the horizontal hydraulic gradient of the shallow unconfined aquifer immediately underlying lower Medano Creek is estimated to be approximately equal to the 1.5% horizontal gradient of Medano Creek itself. This is based on the water levels in wells G-L and well C-1. When the terminus of flow is downstream of the respective locations of wells G-L and well C-1, the water level in these wells is at or just below the ground surface. There is no information available on the horizontal hydraulic gradient of the regional water table.

Borehole Data

Ground Exploration drilled four boreholes in the Medano Creek stream bed from August 17 through 19, 1993.

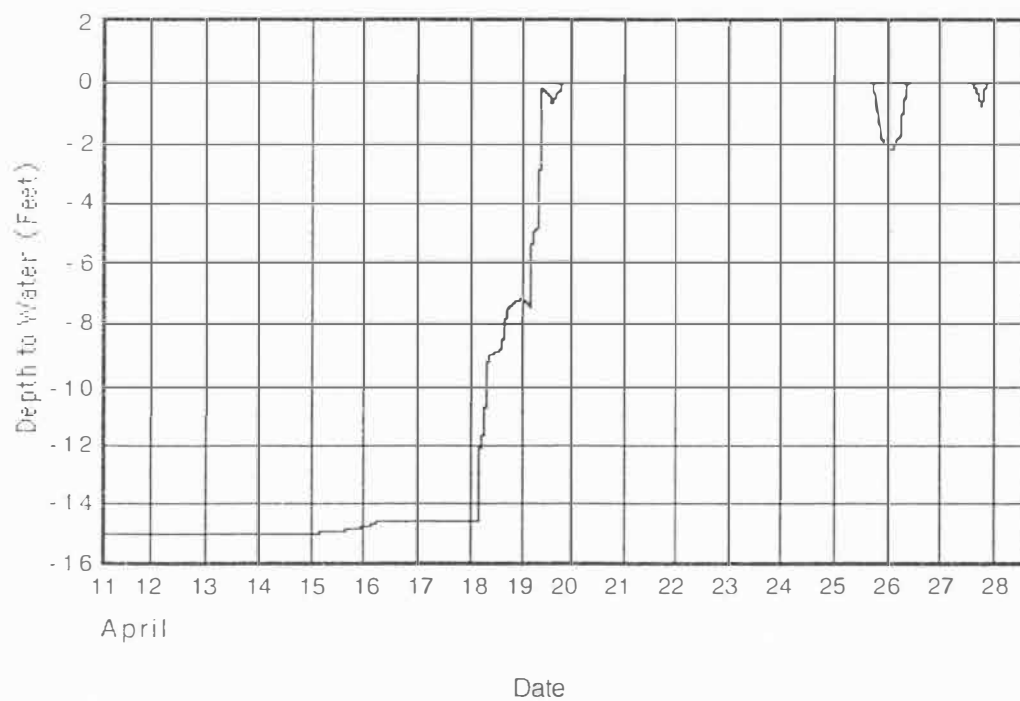


Fig. 7. Depth to water, monitor well C-1.

The wells were drilled with a track-mounted, hollow-stem auger rig. The records of these boreholes are presented in the Appendix, and are the best data available on the subsurface hydrogeology of lower Medano Creek.

Borehole J'''. Borehole J''' is located next to monitor wells J, J' and J''. Borehole J''' was drilled to a total depth of 25 feet (7.6 meters), and was completed with 2-inch PVC casing with a screen 5 feet long at the bottom between 19.28 and 24.28 feet (5.88 and 7.40 meters) below the ground surface (Figure 11, Appendix). The screen was placed below a hard layer 2 feet thick between 17 and 19 feet (5 and 6 meters). A split-spoon sample of this layer yielded silty, fine-to-medium sand with some clay and gravel. On the morning of August 18, 1993, the depths to water in wells J'' and J''' were measured at 0.49 and 22.04 feet (0.15 and 6.72 meters) below the ground surface, respectively. Thus, roughly 4 feet (1 meter) of unsaturated sand lies beneath the hard fine-grained layer, and the vertical hydraulic gradient between boreholes J'' and J''' is downward and the maximum possible, 1.0. In addition, when the hard layer was penetrated during drilling, water circulation was lost and the ground surface collapsed around the borehole, evidence that a downward vertical hydraulic gradient exists across the hard layer. These observations demonstrate that the fine-grained layer acts

as an aquitard that separates an upper, perched aquifer from a lower, unconfined aquifer.

Borehole D-1. Borehole D-1 is next to monitor well K, and it was drilled to a total depth of 100 feet (30 meters). Borehole D-1 was completed with 2-inch PVC casing with a screen 20 feet long at the bottom between 77.58 and 97.58 feet (23.65 and 29.74 meters) below the ground surface (Figure 12, Appendix). The screen was placed through a hard layer 4 feet thick between 90 and 94 feet (27 and 28 meters). No sample of the hard layer in borehole D-1 was obtained, but it likely is similar in composition to the hard layer in borehole J'''. Once again, when the hard layer was penetrated during drilling, water circulation was lost and the surface collapsed around the borehole.

The record of borehole D-1 shows two different water levels (Figure 12, Appendix). The upper water level was measured between the PVC casing and the auger flights when the auger flights became stuck during removal at a depth of about 69 feet (21 meters). The depth to water between the PVC casing and the auger flights was measured at approximately 41 feet (12 meters) below the ground surface. The lower water level was measured inside the PVC casing. The depth to water in the casing was measured at approximately 69 feet (21 meters) below the ground surface.

Water could be heard cascading down the inside of the PVC casing, evidence that water was flowing from an upper aquifer into a lower aquifer through the well screen. Thus, the water level inside the PVC casing cannot be regarded as an accurate representation of the head in the lower aquifer. The water level in this well represents an average water level between the upper aquifer and the lower aquifer, and is a function of the elevation difference between the water levels in the two aquifers and the hydraulic conductivity of the lower aquifer. Water also could be heard cascading down the inside of the auger flights, evidence that the water level between the auger and the PVC casing also represents an average water level between the upper of the two aquifers the well screen is completed across, and the perched aquifer that monitor well K is completed into.

All of the observations noted in the three preceding paragraphs demonstrate that the hard layer encountered in borehole D-1 also acts as an aquitard. In this case, the aquitard separates an upper unconfined aquifer from a lower confined aquifer. The aquitard encountered in borehole J''' pinches out the northwest.

Borehole D-1'. Borehole D-1' was drilled within a few feet of borehole D-1 to try to free the auger flights that became stuck when D-1 was drilled. Borehole D-1' was

drilled to a total depth of 100 feet (30 meters) (Figure 13, Appendix). It encountered the same stratigraphic units as borehole D-1. Borehole D-1' was completed with 2-inch PVC casing with a 5-foot-long screen at the bottom between 94.17 and 99.17 feet (28.70 and 30.23 meters) below the ground surface.

The depth to water in D-1' was measured at approximately 91 feet (28 meters) below the ground surface, which is 3 feet above the base of the low-hydraulic-conductivity layer, evidence that the lower aquifer is confined. This water level probably represents the head in the lower confined aquifer, but there is a slight possibility that the low-hydraulic-conductivity confining layer did not seal around the well casing. If so, water may be flowing down the outside of the PVC casing from the unconfined and/or perched aquifer(s) into the lower aquifer, which would mean that the water level in D-1' represents a head greater than the true head in the lower aquifer. The vertical hydraulic gradient between boreholes D-1 and D-1' is also downward and the maximum possible, 1.0.

Borehole D-2. Borehole D-2 is roughly midway between monitor well K and monitor well C-1. It was drilled to a total depth of 50 feet (15 meters) (Figure 14, Appendix). No PVC casing was installed in borehole D-2 because it was

not drilled deep enough to intercept any low-hydraulic-conductivity layers and, therefore, no hydrologically significant stratigraphic units were encountered. Water was encountered at a depth of approximately 6 feet (2 meters).

Constant-Head Permeameter Tests

Surface sand samples were collected with a shovel at depths of 1 to 2 feet (0.5 meter) near monitor wells G and M. The samples from the area near wells G and M have been used to obtain laboratory measurements of saturated hydraulic conductivity using a constant-head permeameter. The saturated hydraulic conductivity was calculated with the following equation:

$$K = VL/Ath \quad (\text{Fetter, 1988, p. 128})$$

where V is the volume of water discharging in time t, L is the length of the sample, A is the cross-sectional area of the sample, h is the hydraulic head, and K is the saturated hydraulic conductivity.

Five constant-head permeameter experiments were run with samples from the area around monitor wells G-M. Table 1 lists the results of these experiments. The arithmetic mean of the saturated hydraulic conductivity values calculated from these experiments was 1.2×10^4 ft/yr (0.011 cm/sec). The agreement between the five experiments was excellent, with a standard deviation of 2.2×10^3 ft/yr (0.0019 cm/sec). The experimental values of saturated

hydraulic conductivity are also in agreement with the expected values of saturated hydraulic conductivity for a clean sand (Freeze and Cherry, 1979, Table 2.2, p. 29).

Table 1. Constant-Head Permeameter Test Measurements and Results

SAMPLE FROM LOCATION	WELL J	WELL J	WELL I	WELL I	PICNIC AREA
HYDRAULIC HEAD	0.37 ft	0.45 ft	0.48 ft	0.46 ft	0.5 ft
LENGTH OF SAMPLE	1.36 ft	1.35 ft	1.40 ft	1.36 ft	1.37 ft
TIME	2hrs	4hrs	1.42 hrs	2 hrs	2 hrs
VOLUME OF DISCHARGE	8.5×10^{-3} ft ⁻³	1.5×10^{-2} ft ⁻³	6.3×10^{-3} ft ⁻³	1.1×10^{-2} ft ⁻³	8.5×10^{-3} ft ⁻³
CROSS-SECTION AREA OF SAMPLE	9.98×10^{-3} ft ²	9.98×10^{-3} ft ²	9.98×10^{-3} ft ²	9.98×10^{-3} ft ²	9.98×10^{-3} ft ²
HYDRAULIC CONDUCTIVITY	1.4×10^4 ft/yr	9.5×10^3 ft/yr	1.1×10^4 ft/yr	1.3×10^4 ft/yr	1.0×10^4 ft/yr

CHAPTER III

DATA ANALYSIS

Hydrostratigraphy

Based on the detailed logs of boreholes J''', D-1, D-1', and D-2, there appear to be five important hydrostratigraphic units underlying the lower Medano Creek stream channel within 100 feet (30 meters) of the ground surface. The first is a perched aquifer overlying the second, an aquitard between 17 and 19 feet (5 and 6 meters) in borehole J'''. The third is an unconfined aquifer located between the upper and lower aquitards. The fourth is an aquitard between 90 and 94 feet (27 and 29 meters) in boreholes D-1 and D-1', and the fifth is the confined aquifer underlying the lower aquitard.

The two aquitards play a major role in the hydrologic interaction between Medano Creek and the three aquifers, but there is no reliable information on their areal extent. Although the upper aquitard was not encountered in boreholes D-1 and D-1', the difference in the water level between the auger flights and the PVC casing in borehole D-1, and a water level near the surface in monitor well K, as well as the presence of cascading water inside the auger, suggests that a shallow, low-hydraulic-conductivity layer exists at this location. However, it seems fairly certain that the shallow aquitard does not extend very far

downstream of borehole D-1, as nothing similar to it was encountered in borehole D-2. In addition, the areal extent of the lower aquitard in boreholes D-1 and D-1' is unknown because neither of the other logged boreholes was drilled deeper than 50 feet (15 meters).

Correlation of Surface Water and Groundwater

The water-level data are limited to the upper perched aquifer immediately underlying lower Medano Creek with three additional points of water-level data contained in the logs of boreholes J''', D-1, and D-1' (Figures 11, 12, and 13). The relationship between the location of the flow terminus and the shallow-groundwater system underlying lower Medano Creek appears to be fairly simple. The upper perched aquifer has a limited volume. The upper perched aquifer is bounded below by an aquitard near 15 to 20 feet (5 to 6 meters) in depth. The advance of Medano Creek rapidly fills the upper aquifer during the snowmelt season along the portion of channel where this aquitard is present in the subsurface. Even where the upper aquitard is absent, Medano Creek would probably fill up the underlying unconfined aquifer in several days. This assumption is based on the filling of the entire thickness of the perched aquifer at well C-1 in 1 day during April of 1992 and the water-level rise of 3.7 feet in well J in 4 days during

April of 1993. Water levels in the upper perched aquifer only declined a modest 4 to 15 feet (1.2 to 4.6 meters) during the time between successive runoff periods. It is impossible to correlate the surface-water flow of lower Medano Creek with water levels in the two deeper aquifers due to the paucity of water-level data available for them. In addition, it is not known if the lower confined aquifer represents the regional water table, or if one or more additional aquitards lie between the lower confined aquifer and the regional water table. Thus, for these reasons it is not known what effect the annual runoff event has on the regional water table.

Conceptual Models

Lower Medano Creek Model

Because the areal extent and number of the fine-grained layers is unknown, an accurate conceptual model of the hydrogeologic system underlying lower Medano Creek is difficult to develop. The conceptual model of lower Medano Creek based on the borehole records can be envisioned as a complex hydrogeologic system consisting of several thin low-hydraulic-conductivity layers with limited areal extent (Figure 8). This is similar to the conceptual model of the Alamosa Basin developed by Hearne and Dewey (1988). The conceptual model of the Alamosa Basin consists of a complex

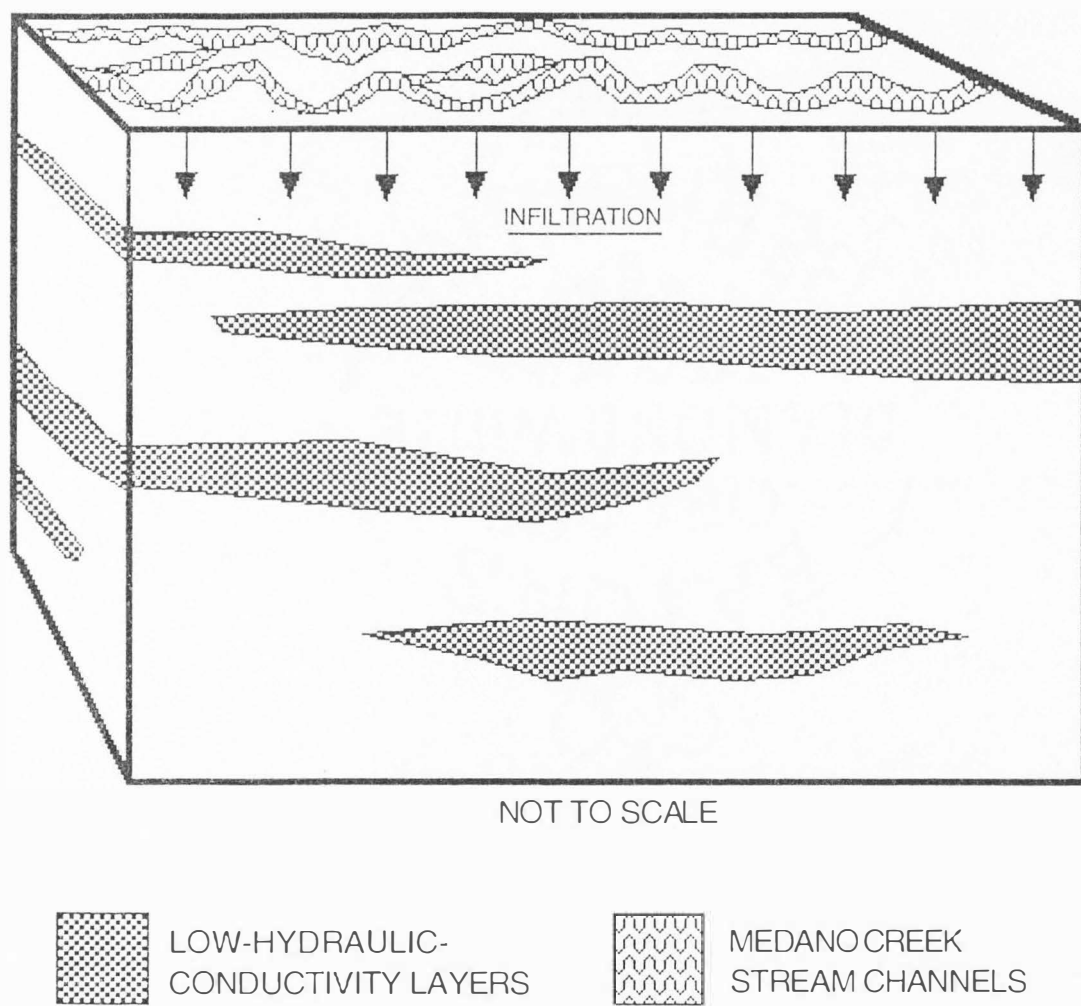


Fig. 8. Lower Medano Creek conceptual model.

system of interlayered aquifers and leaky confining layers, with each aquifer having a hydraulic head unique to the individual aquifer. The conceptual model of lower Medano Creek that will be used in this report also consists of low-hydraulic-conductivity layers interbedded with aquifers having unique hydraulic-head values.

It is not practical to develop a numerical model based on this conceptual model because of the complexity of the conceptual model. In addition, the actual number, location, depth, and areal extent of the low-hydraulic-conductivity layers under Medano Creek are unknown.

Single-Confining-Layer Model

In their report on the Alamosa Basin, Hearne and Dewey (1988) mentioned that a single-confining-layer model is useful in describing the general hydrogeologic features of the aquifer system. The single-confining-layer conceptual model that will be used in this report replaces the complex system of thin low-hydraulic-conductivity layers with a single, continuous confining layer 100 feet (30 meters) thick (Figure 9). This model assumes that the hydraulic effect of the single low-hydraulic-conductivity confining layer will be similar to the complex system of multiple, discontinuous, thin, low-hydraulic-conductivity layers underlying Medano Creek. This assumption seems reasonable for two reasons.

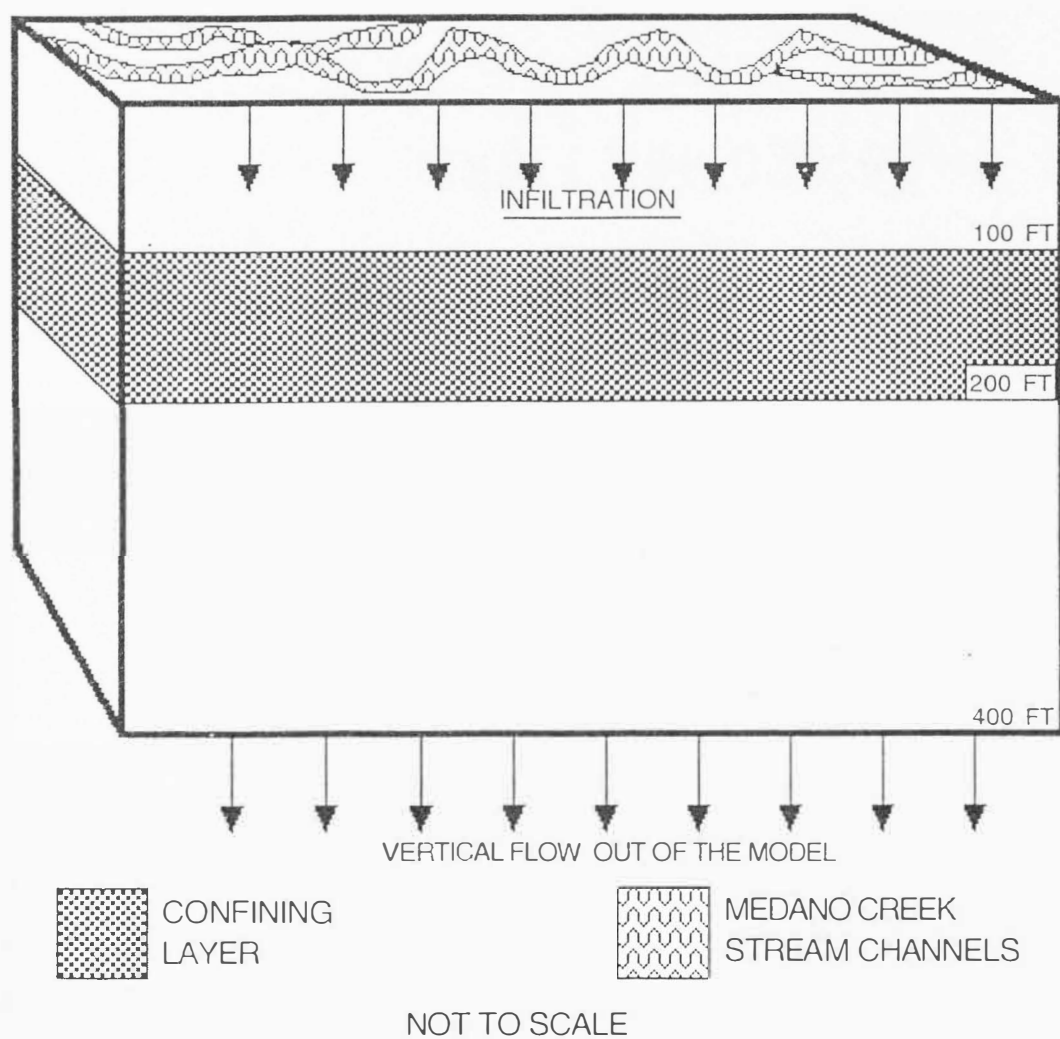


Fig. 9. Single-confining-layer model.

The first reason is the primarily vertical flow direction of groundwater underlying lower Medano Creek. The borehole records show vertical hydraulic gradients of 1.0 (which is the maximum gradient possible) between wells J'' and J''' and between wells D-1 and D-1', while the horizontal hydraulic gradient is estimated to be approximately equal to the stream gradient of lower Medano Creek, which is 1.5%. Although the horizontal gradient does not represent the gradient of the regional water table, the two gradients are likely similar to each other. Thus, the primary direction of groundwater flow underlying lower Medano Creek is vertical.

The second reason why the single-layer model is probably a reasonable approximation of the complex system of thin low-hydraulic-conductivity layers underlying lower Medano Creek is that the two conceptual models have the same effect on the hydraulic conductivity of the entire system. The horizontal orientation of the confining layers makes the overall vertical hydraulic conductivity of the system much smaller than the average horizontal hydraulic conductivity. The single confining layer proposed here has a similar effect on the system.

The single confining layer in the model is between 100 and 100 feet (30 and 60 meters) in depth. The thickness of 100 feet (30 meters) of the confining layer and the

placement of the top of the confining layer 100 feet (30 meters) below the ground surface were chosen because the use of vertical thicknesses of less than 100 feet (30 meters) requires many more node points to maintain model stability. However, the primarily vertical direction of groundwater flow under lower Medano Creek makes the vertical thickness and placement of the confining layer unimportant. This is due to the fact that the vertical rate of flow is a function of the hydraulic conductivity and the hydraulic head.

Numerical Modeling

The numerical model has been developed from the program UNSAT, written by Neuman et al. (1972). The version used for this investigation was most recently revised by Bloomsburg and Rinker (1983). This program was chosen because: 1) it is readily available, 2) it is well documented by previous use, 3) it is simple to use, 4) it can simulate flow in both the unsaturated and saturated zones, and 5) it can handle a wide range of boundary conditions. The ability of the program to simulate flow in the unsaturated zone and the wide range of boundary conditions available are necessary for this investigation.

Construction of the Finite-Element Mesh

To transform a conceptual model into a numerical model, a finite-element mesh is necessary. The first step in constructing a finite-element mesh is to construct to scale a cross section of the area to be modeled. The cross section must include the boundary conditions, the interfaces between each significantly different hydrogeologic material, and the hydraulic properties of each material. The finite-element mesh must then be constructed by placing nodes at each boundary and interface. The quadrilaterals formed by four adjacent nodes need to be more or less equidimensional or the model becomes unstable (Bloomsburg and Rinker, 1983).

The conceptual model of lower Medano Creek utilized is a two-dimensional, longitudinal cross section along the creek. The distance along Medano Creek from the Castle Creek flume to the terminus of flow on the 1990 aerial photographs is approximately 32,000 feet (9,700 meters). The finite-element mesh for a conceptual model 32,000 feet (9,700 meters) long with numerous thin confining layers would require thousands of node points to maintain model stability. In addition, the actual number, location, depth, and areal extent of the confining layers under Medano Creek are unknown. For these reasons, the simplified single-confining-layer conceptual model has been adopted for

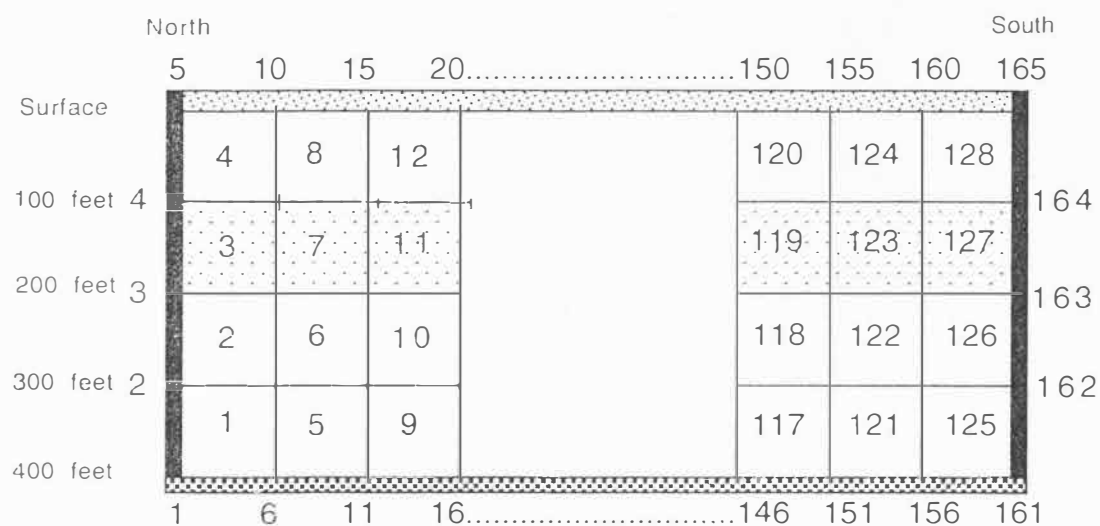
numerical modeling. The single-confining-layer model is practical to use, and it is a reasonable approximation of the hydrogeologic conditions beneath lower Medano Creek. The finite-element mesh constructed for the single-confining-layer numerical model contains 165 nodes and 128 elements (Figure 10).

Boundary Conditions

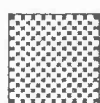
The program UNSAT allows the following external boundary conditions: 1) prescribed pressure head, 2) prescribed flux normal to the boundary, 3) evapotranspiration/infiltration where the program will calculate the actual flux, and 4) seepage faces.

The upper (surface) boundary of the model is an infiltration boundary where the program calculates the actual flux. The lower boundary of the model is a prescribed pressure-head boundary, and both of the vertical boundaries at either end of the model are prescribed flux boundaries (Figure 10).

Upper boundary. An infiltration boundary where the program calculates the actual flux was chosen along the top of the model to simulate the infiltration boundary that exists along lower Medano Creek. The infiltration boundary was also chosen to allow the numerical model to be calibrated. The reasons for selecting an infiltration boundary along the top of the model will be explained



NOT TO SCALE



CONSTANT-HEAD
BOUNDARY



MODEL-CONTROLLED
INFILTRATION BOUNDARY



IMPERMEABLE
BOUNDARY



LOCATION OF THE PERCHING
ZONE IN THE MODEL

NODES ARE REPRESENTED BY
THE EXTERIOR NUMBERS

ELEMENTS ARE REPRESENTED BY
THE INTERIOR NUMBERS

Fig. 10. Finite-element mesh for numerical model.

further in discussion of model calibration.

Vertical boundaries. The prescribed flux boundaries at both ends of the model have been specified as zero flux or no-flow boundaries. Although vertical impermeable boundaries do not actually exist along Medano Creek at the Castle Creek flume and at the terminus of flow, the impermeable boundaries used in the model are reasonable approximations of the actual hydrogeologic system because of the primarily vertical flow of groundwater beneath lower Medano Creek. The horizontal component of groundwater flow is negligible when compared to the vertical component and therefore is ignored. When horizontal flow is allowed through the upstream and downstream ends of the model, the final infiltration totals are identical to the results obtained using impermeable boundaries at the ends. However, due to the model length of 32,000 feet (9,700 meters), the program forms unnatural infiltration patterns when horizontal groundwater flow is allowed through the ends of the model. The impermeable boundaries at the ends of the model create reasonable infiltration patterns.

Lower boundary. The lower boundary of the model is a prescribed pressure-head boundary. The actual lower hydrogeologic boundary underlying lower Medano Creek is a bedrock contact that forms a nearly impermeable boundary. There are two reasons why an impermeable boundary on the

bottom of the model was not used. The first reason is that the depth of the bedrock contact beneath lower Medano Creek is unknown. The second reason is the result of a limitation of the modeling program. The pressure head cannot be controlled on a prescribed flux or impermeable boundary. The purpose of the numerical modeling is to evaluate the effects a lowering of the regional water table will have on lower Medano Creek. Lowering the pressure head at the bottom of the model is the best way to simulate a lowering of the regional water table. In addition, a prescribed pressure-head boundary allows a vertical flux of groundwater downward out of the model. This agrees with the predominantly vertical direction of groundwater flow beneath lower Medano Creek.

The pressure-head values used on the lower boundary are based on the water level in borehole D-1'. The water level in this borehole is 91 feet (28 meters) below the surface. Thus, it is assumed that the regional water table lies at approximately 91 feet (28 meters) below the ground surface. The actual regional water table may be deeper than this, but there is no information available on water levels at depths greater than 100 feet (30 meters) beneath lower Medano Creek.

The location of the potentiometric surface is based on the water level in borehole D-1' and an assumed horizontal

gradient of 0.001. The horizontal gradient of 0.001 was used to calculate the initial pressure-head values along the lower boundary. The actual horizontal hydraulic gradient of the regional water table is unknown. For the model to reproduce actual infiltration conditions, the surface gradient of lower Medano Creek is decreased from the actual gradient of 0.015 to horizontal. If the surface gradient is not changed, a gradient of 0.016 would be used for the regional water table. The gradient of 0.001 is not intended to represent the actual hydraulic gradient of the regional water table. Rather, it is intended to impart a small horizontal-flow component to the model. Without this small horizontal-flow component, the model results are unrealistic, as the upper boundary node points alternate between large infiltration values and large seepage values between adjacent surface node points when the model is run. With a horizontal gradient of 0.001, the potentiometric surface at node point 1 is 75 feet (23 meters) below the surface, the potentiometric surface at node point 81 (node point 81 is located at borehole D-1') is 91 feet (28 meters) below the surface, and the potentiometric surface at node point 161 is 107 feet (33 meters) below the surface. Thus, the potentiometric surface drops 32 feet (10 meters) total, 1 foot for every lower-boundary node point between node point 1 and node point 161.

Hydraulic Properties

The following hydraulic properties are required entries for each of the two materials used in the numerical model: 1) horizontal hydraulic conductivity, 2) vertical hydraulic conductivity, 3) effective porosity, 4) specific storage, 5) a table of relative hydraulic conductivity versus volumetric moisture content, and 6) a table of pressure head as a function of volumetric moisture content. Two materials have been used in the numerical model: 1) the sand overlying and underlying the confining layer, and 2) the confining layer itself.

The value for the horizontal hydraulic conductivity of the sand was calculated from the constant-head permeameter-test data discussed previously. The constant-head permeameter tests were conducted on disturbed samples in the laboratory. When the samples were disturbed, all of the layering in the samples was destroyed. Thus, the results of the test more closely represent the horizontal hydraulic conductivity of the sand. The calculated value from table 1 of horizontal hydraulic conductivity is approximately $1 * 10^4$ ft/yr ($1 * 10^{-2}$ cm/sec).

The vertical hydraulic conductivity of the sand is estimated to be one order of magnitude smaller than the horizontal hydraulic conductivity, or $1 * 10^3$ ft/yr ($1 * 10^{-3}$ cm/sec). This estimate is based on the fact that in

horizontally layered materials the vertical hydraulic conductivity is much smaller than the horizontal hydraulic conductivity (Freeze and Cherry, 1979). A one order-of-magnitude difference between the horizontal hydraulic conductivity and the vertical hydraulic conductivity is a reasonable approximation. When the model was run with equal values of vertical and horizontal hydraulic conductivity, groundwater began flowing upward at some of the lower-boundary node points, and downward at adjacent lower-boundary node points. This was obviously unreasonable.

The vertical and horizontal hydraulic conductivities of the confining layer were calculated during the calibration procedure. The values of hydraulic conductivity used in the confining layer will be included in the discussion of the calibration procedure.

The values of effective porosity and specific storage used are not critical to the model. The model was run with different values of effective porosity and specific storage in both the sand and the confining layer, and there was no difference in the results.

An effective porosity of 0.35 was used for both materials. This value is based on expected porosity ranges for sand and the effective pore fraction for sediments with interconnected pores as discussed in Fetter (1988, pp. 68-85).

A specific-storage value of $1.0 * 10^{-5} \text{ ft}^{-1}$ was used for both materials. This value is based on specific-storage estimates in Fetter (1988, p. 106).

The table of relative hydraulic conductivity versus volumetric moisture content used for the sand layer in the model is from Bear (1979, Figure 6.16, p. 210). This table is for an unsaturated sand. The values in this table form a curve, which is typical for all tables of relative hydraulic conductivity versus volumetric moisture content (Brooks and Corey, 1964). In order for the model to run well, the curve must be smoothed. Thus, only two points near the ends of the curve were used to make the table. The values of relative hydraulic conductivity represent a percentage of the saturated hydraulic conductivity of the material.

The values used were a relative hydraulic conductivity of $1.0 * 10^{-4}$ at a volumetric moisture content of 0.08, and a relative hydraulic conductivity of 1.0 at a volumetric moisture content of 0.35. The value of 0.08 was chosen for three reasons: 1) it was chosen in order to make a best fit straight line through the majority of the curve; 2) it was a point where a value could be accurately picked from the curve; and 3) it represents the end point of the straight portion of a curve that becomes asymptotic. The model interpolates linear values between the two points.

The table of pressure head as a function of volumetric moisture content that was used for the sand layer in the model is from Freeze and Cherry (1979, Figure 2.13, p. 42). Again, the values in this table form a curve that is typical for all materials (Brooks and Corey, 1964). Two points were chosen for the same reasons listed for relative hydraulic conductivity in the discussion above. The values are a pressure head of -8.2 feet (-2.5 meters) at a volumetric moisture content of 0.02, and a pressure head of 0 at a volumetric moisture content of 0.35. The model makes a linear interpolation between the two points.

A table of relative hydraulic conductivity versus volumetric moisture content and a table of pressure head as a function of volumetric moisture content also are required for the confining layer. However, the tables are only used by the model if the material becomes unsaturated. As the confining layer never became unsaturated, the same tables were used for the sand and the confining layer.

Model Calibration

The numerical model was calibrated such that the total infiltration rate at the 33 nodes along the top of the model was equal to the previously calculated infiltration rate along lower Medano Creek of 66 ft/yr (20 m/yr). The model output contains infiltration values for each surface-boundary node point. The total infiltration along the top

of the model was calculated at steady-state conditions after the model had been run for a simulated time of 1 year. The model reached steady-state conditions in less than 1 year.

There are two main controls on the infiltration rate of lower Medano Creek. The first is the vertical hydraulic gradient which, in this case, is controlled by the potentiometric surface created by the prescribed pressure-head boundary along the bottom of the model. The second is the hydraulic conductivity of the entire lower Medano Creek hydrogeologic system, especially the vertical hydraulic conductivity of the confining layer. The flux of groundwater through hydrogeologic systems is controlled by the layer with the lowest hydraulic conductivity. As the primary direction of groundwater flow underlying lower Medano Creek is vertical, the vertical hydraulic conductivity of the confining layer has a very large effect on the flux through the hydrogeologic system. The vertical hydraulic conductivity of the confining layer between 100 and 200 feet (30 and 60 meters) is the lowest hydraulic conductivity in the system, and therefore it forms a barrier to vertical groundwater flow.

The program was run with different values for the vertical hydraulic conductivity of the confining layer until the total infiltration rate at the 33 nodes along the

upper boundary of the model was equal to 66 ft/yr (20 m/yr) under steady-state conditions. The model was calibrated with a value of 7.72 ft/yr (235 cm/yr) for the vertical hydraulic conductivity of the confining layer. During the calibration procedure, the horizontal hydraulic conductivity of the confining layer was always one order of magnitude larger than the vertical hydraulic conductivity. Thus, in the calibrated model, the horizontal hydraulic conductivity of the confining layer was 77.2 ft/yr (2,350 cm/yr). These values of hydraulic conductivity are between the expected values for a silty sand and a silty loess (Freeze and Cherry, 1979, Table 2.2, p. 29), which is to be expected given the materials found during the drilling of boreholes J''', D-1, D-1', and D-2 in the lower Medano Creek area. The fact that the values calculated during the calibration process match the expected values for similar materials in the published literature increases the level of confidence in the model's validity.

Results

After calibration, the model was used to predict the effects of lowering the regional water table. Regional water-table declines of 150 feet (46 meters) have been projected if the proposed groundwater withdrawals take place. Therefore, the calibrated model was run with the pressure-head values along the lower boundary of the model

lowered 150 feet (46 meters) to predict the effects of the proposed groundwater withdrawals. This corresponds with a potentiometric surface 225 feet (69 meters) below the surface at node point 1, a potentiometric surface 241 feet (74 meters) below the surface at node point 81 (the location of borehole D-1'), and a potentiometric surface 257 feet (78 meters) below the surface at node point 161. Once again, the potentiometric surface drops 1 foot for every node point along the lower boundary between node point 1 and node point 161, and forms a linear surface between node point 1 and node point 161.

The model was run for a simulated time of 2 years. This was long enough for the model to reach steady-state conditions. Under steady-state conditions, the node points at the base of the confining layer were unsaturated. This includes every fifth node point starting with node point 3 (i.e., nodes 3, 8, 13, 18....158 and 163). The terminus-of-flow location was then calculated by adding the infiltration rate at each surface node, from node point 1 downstream, until the total infiltration rate of the model after lowering the potentiometric surface equaled the total infiltration rate of 66 ft/yr (20 m/yr). The terminus of flow retreated 21,000 feet (6,400 meters) after the potentiometric surface was lowered 150 ft (46 m). This corresponds to a location between node points 55 and 60,

approximately 10,500 feet (3,200 meters) downstream from the Castle Creek flume. It should be noted that this location is upstream of the picnic area.

CHAPTER IV

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

As part of this investigation, the available hydrogeologic data for the San Luis Valley, the Great Sand Dunes National Monument, and Medano Creek were reviewed. Very little hydrogeologic data are available for depths greater than 20 feet (6 meters) in the immediate vicinity of the study area. However, the available hydrogeologic data on the San Luis Valley were useful in developing a conceptual model of the study area.

Additionally, surface-water and water-level data collected in the Great Sand Dunes National Monument as part of the larger investigation were reviewed. These data included flume data, shallow-monitoring-well data, and terminus-of-flow data. The flume data included: 1) stream discharge data from the Boundary flume from June 28, 1991, to November 7, 1992, and from March 7, 1993, to May 25, 1993; and 2) stream-discharge data from the Castle Creek flume from June 28, 1991, to April 9, 1992. The shallow-monitoring-well data included: 1) water levels in well J from September 28, 1991, to April 10, 1992, and from March 19 to May 10, 1993; 2) water levels in well L from September 28, 1991, to January 2, 1993; and 3) water levels

in well C-1 from April 10 to April 28, 1992. The terminus-of-flow location is recorded from March 19 to April 17, 1993, with one additional measurement taken on April 26, 1993.

Some additional data were obtained from drilling four additional boreholes, and from additional water-level measurements and stream-flow observations. The water levels were measured in each of the four boreholes. The water level was also measured in well K, which is near boreholes D-1 and D-1', and in well J'', which is near borehole J'''. At the time of these measurements, the terminus of flow was downstream of wells K and J'''. These data were correlated in order to better understand the interactions between the surface water, the shallow aquifer underlying lower Medano Creek, and the deeper groundwater systems along lower Medano Creek. The records of the four boreholes also provide the best data available on the subsurface hydrogeology of lower Medano Creek.

The infiltration rate of lower Medano Creek was estimated with two separate methods: 1) Stream-bed losses were estimated by taking discharge measurements at two different locations on lower Medano Creek and then calculating the loss in discharge by subtracting the downstream discharge measurement from the upstream discharge measurement; and 2) calculating the infiltration

rate of lower Medano Creek with a peak discharge measurement from the Castle Creek flume, the area of lower Medano Creek from aerial photographs of the area taken near the time of the peak discharge, and estimations of evapotranspiration rates from Hearne and Dewey (1988).

Constant-head permeameter tests were conducted on sand samples collected near the ground surface along lower Medano Creek. The results of these tests were compared with the expected values of hydraulic conductivity for similar materials published in the literature. The values of hydraulic conductivity calculated matched the values of hydraulic conductivity in the literature.

All of the information collected was then used to develop a conceptual model of lower Medano Creek. The conceptual model consisted of a complex system of thin low-hydraulic-conductivity layers. This model is similar to the model developed by Hearne and Dewey (1988) for the San Luis Valley. Unfortunately, this conceptual model is not practical for numerical modeling. Instead, a simplified three-layer conceptual model was used to simulate the complex hydrogeologic system. This three-layer model is similar to a simplified model used by Hearne and Dewey (1988) to describe the general characteristics of the San Luis Valley hydrogeologic system.

The program UNSAT was used for numerical modeling.

After calibration, the numerical model was used to predict the effect that a lowering of the regional water table would have on the surface flow of lower Medano Creek.

Conclusions

From the borehole records of four new boreholes, there appear to be five important hydrostratigraphic units underlying the lower Medano Creek stream channel within the upper 100 feet (30 meters). The first is a perched aquifer overlying the aquitard located between 17 and 19 feet (5 and 6 meters) in borehole J'''. The second is this aquitard itself. The third is the unconfined aquifer between the upper and lower aquitards. The fourth is the aquitard between depths of 90 and 94 feet (27 and 29 meters) in boreholes D-1 and D-1', and the fifth is the confined aquifer underlying the lower aquitard. Unfortunately, there is no reliable information on the areal extent of the aquitards.

The water levels in monitor wells J and C-1 both rise rapidly to their annual maximum level in response to the arrival of the terminus of flow (see Figures 6 and 7). In addition, a graph of the position of the flow terminus and the discharge of Medano Creek at the Boundary flume through time (Figure 3) shows that the two plots are nearly parallel to one another. Thus, the water table in the perched aquifer in the lower Medano Creek area appears to

be controlled by the terminus of flow, which in turn is controlled by the discharge of lower Medano Creek. There are not enough water-level data available on the deeper aquifers to establish a correlation between lower Medano Creek and the regional water table.

As mentioned previously, two different methods were used to estimate the infiltration rate of lower Medano Creek. The agreement between the two estimates was very good. Because the two methods produced similar results, there is a high level of confidence in the infiltration-rate estimations.

There were two measurements made of the vertical hydraulic gradient underlying lower Medano Creek. One was made between wells J'' and J''', and the other was made between boreholes D-1 and D-1'. The vertical hydraulic gradient in both locations was 1.0 downward. The value measured between wells J'' and J''' is accurate. However, the value measured between boreholes D-1 and D-1' may be in error because the well screen in borehole D-1 is completed through a confining layer. In either case, the downward vertical hydraulic gradient underlying lower Medano Creek is very steep. The horizontal hydraulic gradient of the shallow unconfined aquifer immediately underlying lower Medano Creek is estimated to be approximately equal to the 1.5% gradient of Medano Creek itself. The horizontal

hydraulic gradient of the regional water table is unknown, but it is assumed to be similar to the horizontal hydraulic gradient of the shallow unconfined aquifer.

Constant-head permeameter tests conducted on sand samples collected near the ground surface along lower Medano Creek produced values of hydraulic conductivity that are in agreement with published estimates of hydraulic conductivity for a clean sand (Freeze and Cherry, 1979, Table 2.2, p. 29). In addition, hydraulic-conductivity values calculated for the confining layer during numerical-model calibration were in agreement with values of hydraulic conductivity for materials found during drilling in the lower Medano Creek area (Freeze and Cherry, 1979).

The numerical-modeling results suggest that a lowering of the regional water table may move the position of the terminus of flow in lower Medano Creek a considerable distance upstream. The magnitude of the recession of the terminus of flow is uncertain. The predictions of the numerical model should be used with care. It must be emphasized that the modeling results are crude approximations because of the paucity of data available. Specifically, there are no hydrogeologic data available at depths greater than 100 feet (30 meters) beneath lower Medano Creek, and very little information is available for depths greater than 20 feet (6 meters). The position of the

regional water table has not been established, and it is not known what effect the annual runoff event has on the regional water table. In addition, the conceptual model used is simplistic, and can only be considered a crude approximation of the actual complex hydrogeology of the system.

Recommendations

Further information should be gathered in the Great Sand Dunes National Monument to improve the level of confidence in the predictions of numerical modeling. This information will also help increase the accuracy of the predictions. Two key pieces of information that need to be gathered are the depth to bedrock beneath lower Medano Creek and the depth to the regional water table. The most reliable method of obtaining this information is to drill, log, and test boreholes.

A dual-wall, reverse-circulation, rotary-drilling method using booster compressors probably would provide the best chance for successful borehole completion to depths of 800 to 1,000 feet (244 to 305 meters) (Driscoll, 1986). While completion depths of 800 to 1,000 feet (244 to 305 meters) are probably not necessary, they can be reached. This drilling method is recommended for use in the lower Medano Creek area for the following reasons: 1) representative formation samples can be obtained; 2) rapid

penetration rates are possible; 3) lost circulation problems are greatly reduced; and 4) small diameter PVC casing (1 to 2 inches) can be installed while the casing used during drilling is still in the borehole.

A drill-through, casing-driver drilling method could also be used in the lower Medano Creek area. This drilling method should be able to obtain borehole depths comparable to the dual-wall, reverse-circulation drilling method (Driscoll, 1986). The boreholes may need to be drilled during the off season because the drill-through casing driver is very loud.

An accurate borehole log should be kept during drilling operations, and samples of each hydrogeologically significant unit should be taken. This includes any low-hydraulic-conductivity layers. The samples should be large enough to conduct permeameter tests.

Piezometers should be placed in each borehole with their screened sections completed beneath each hydrogeologically significant low-hydraulic-conductivity layer. If more than one hydrogeologically significant low-hydraulic-conductivity layer is encountered while drilling the borehole, a piezometer nest should be installed. The piezometers need to have an inner diameter large enough to accommodate an electric probe and/or a pressure transducer. The screened sections of the piezometers should be no more

than 5 feet long, and they should be completed a few feet beneath the low-hydraulic-conductivity layer chosen in each borehole. If possible, individual piezometers should be placed beneath each low-hydraulic-conductivity layer in each of the locations listed below. This may require drilling multiple boreholes in each location or installing piezometer nests.

Boreholes should be drilled in the stream channel of lower Medano Creek in three locations: 1) near the maximum terminus of flow, 2) near well C-1, and 3) near the monitor well cluster. These three boreholes will provide information on the hydraulic gradient of the regional water table. They will also provide data to correlate the regional water table with the terminus-of-flow location and with the discharge of lower Medano Creek. Additional boreholes could also be drilled to further define the lateral extent of any low-hydraulic-conductivity layers. Boreholes drilled to define the lateral extent of low-hydraulic-conductivity layers may be the most important, as the low-hydraulic-conductivity layers will have a pronounced effect on the hydrogeologic system. A more complete picture of the hydrogeology underlying lower Medano Creek will be obtained with each borehole.

Ideally, the boreholes should be drilled to the bedrock contact. If the boreholes cannot be drilled to

bedrock, they should be drilled deep enough to confirm the location of the regional water table.

A good geophysical survey is also necessary to establish the location of the bedrock contact in the lower Medano Creek area. A good geophysical survey would be relatively unobtrusive, and it would provide a great deal of information for the price. In the lower Medano Creek area, a large-scale seismic survey utilizing explosives should provide the best results.

After the piezometers are installed, further surface-water data, water-level data, and terminus-of-flow data should be gathered. At least one flume needs to be operating on Medano Creek, and it needs to be instrumented with a data logger. The deep boreholes, especially those in contact with the regional water table, need to be instrumented with a pressure transducer and a data logger. It is important that this information be gathered simultaneously so that the relationship between lower Medano Creek's discharge, the water levels at various depths beneath the creek, and its terminus of flow can be determined.

Laboratory permeameter tests should be conducted on the cuttings collected during drilling to determine the hydraulic conductivity of the confining layers. Pumping tests should be conducted in each different aquifer, with

attention paid to the effects of the pumping test on all of the aquifers to determine the degree of interconnection between them.

Once this information is compiled, a groundwater-modeling specialist should be consulted. With this additional information and greater groundwater-modeling expertise, a much more detailed and realistic model will be obtained.

It is important to realize that the lower Medano Creek area is very complex hydrogeologically. A decision must be made regarding the accuracy of the model needed, and the amount of money that should be invested to obtain a more accurate model. The previous recommendations outline a very ambitious program. Some less expensive alternatives are 1) place a pressure transducer and data logger in borehole D-1 to determine the effect that the creek has on the deeper aquifers, 2) rebuild one of the flumes on Medano Creek and outfit it with a data logger, and 3) correlate the flume data, borehole D-1 data, monitoring-well-cluster data, and terminus-of-flow data. This abbreviated investigation would improve the understanding of the hydrogeology of lower Medano Creek without incurring prohibitive costs. If further drilling operations are conducted, a good geophysical survey should be done initially to select specific areas for future drilling operations. Boreholes

should be drilled as close to the lower Medano Creek floodplain as possible with a big rig without driving it into areas where it may get stuck.

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APPENDIX

RECORD OF BOREHOLE J'''						
Logged by: Tom Lachman & Gregg Hadlock Page 1 of 1						
Project: <u>Great Sand Dunes</u> Location: <u>Next to monitoring well J</u>						
Approximate Ground Surface Elevation: <u>8015 feet</u> Total Depth: <u>25 feet</u>						
Hole Diam: <u>4.25" I.D. 8.5" O.D.</u> Date Started: <u>18 Aug. 1993</u> Date Completed: <u>18 Aug. 1993</u>						
Drilling Method: <u>Hollow Stem Auger</u> Drilling Fluid: <u>None</u> Contractor: <u>Ground Exploration</u>						
Depth (feet)	Lithologic Description	Strat. Plot	Pene. Rate	Water Level	Well Casing	Completion Data
0	Ground Surface					Stick up = 0.72 feet
5	Medium Sand		1			Split-spoon sample taken 17 feet to 18.5 feet
10	Medium Sand		1			
15	Medium Sand with some Gravel		2			Aug. 18 A.M. Water Level = 22.76 feet below Top of Casing
20	Medium Sand		1			
	Hard Layer - Silty Fine to Medium Sand with some Clay and Gravel		2			Aug. 18 P.M. Water Level = 22.71 feet below Top of Casing
25	Medium Sand		1	22 feet		Aug. 19 A.M. Water Level = 23.16 feet below Top of Casing
Vertical Scale 1 in. = 5 ft		Remarks: J''' Total depth = 13.8 feet Water Level = 1.33 feet (Stick up = 0.84 feet)				

Figure 11. Record of borehole J'''

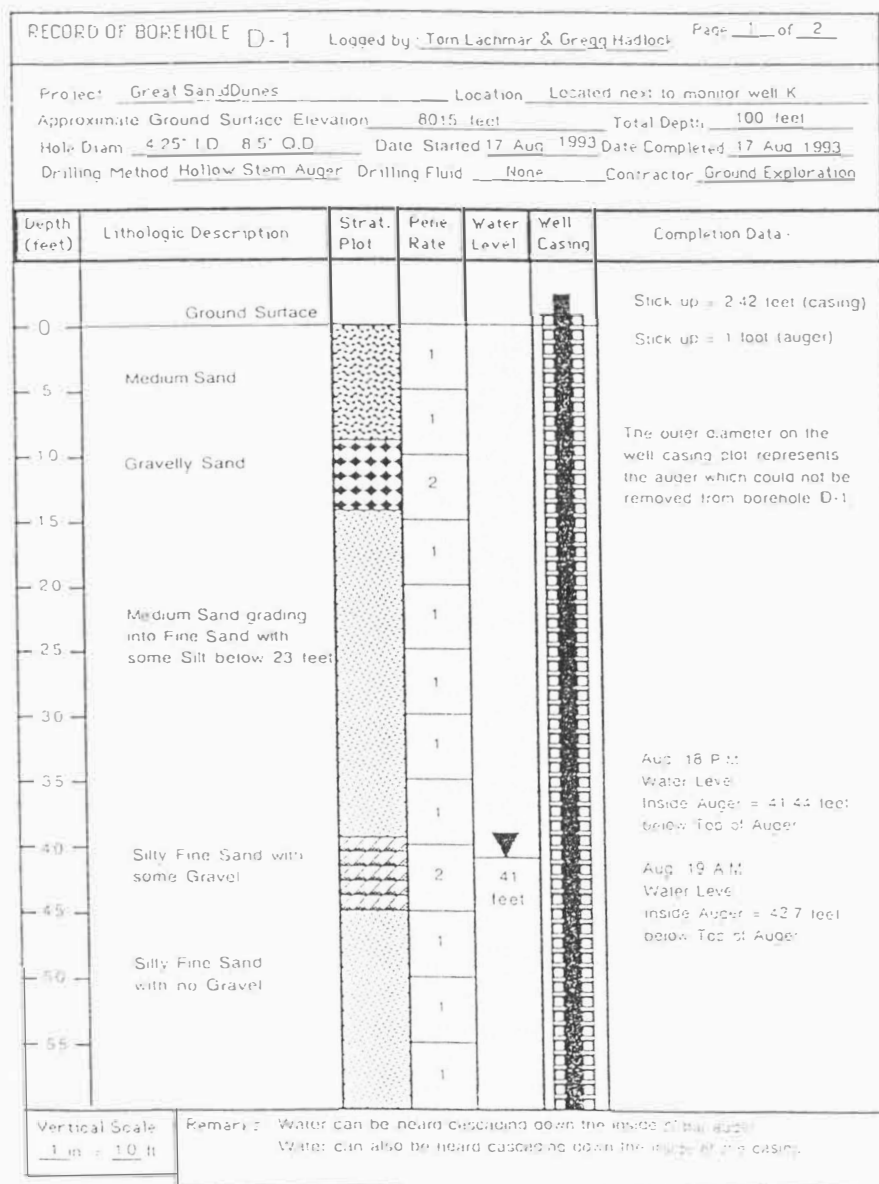


Figure 12. Record of borehole D-1 (page 1.)

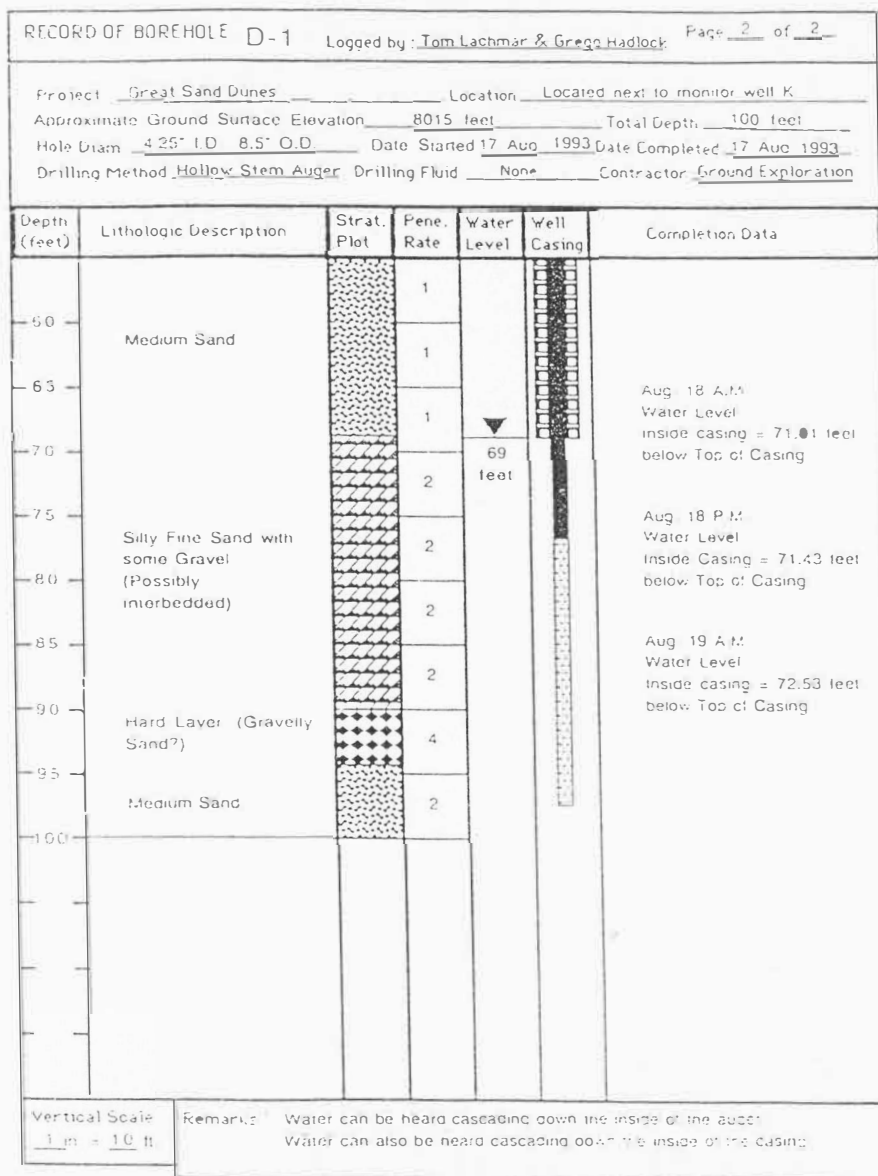


Figure 12. Record of borehole D-1 (page 2.)

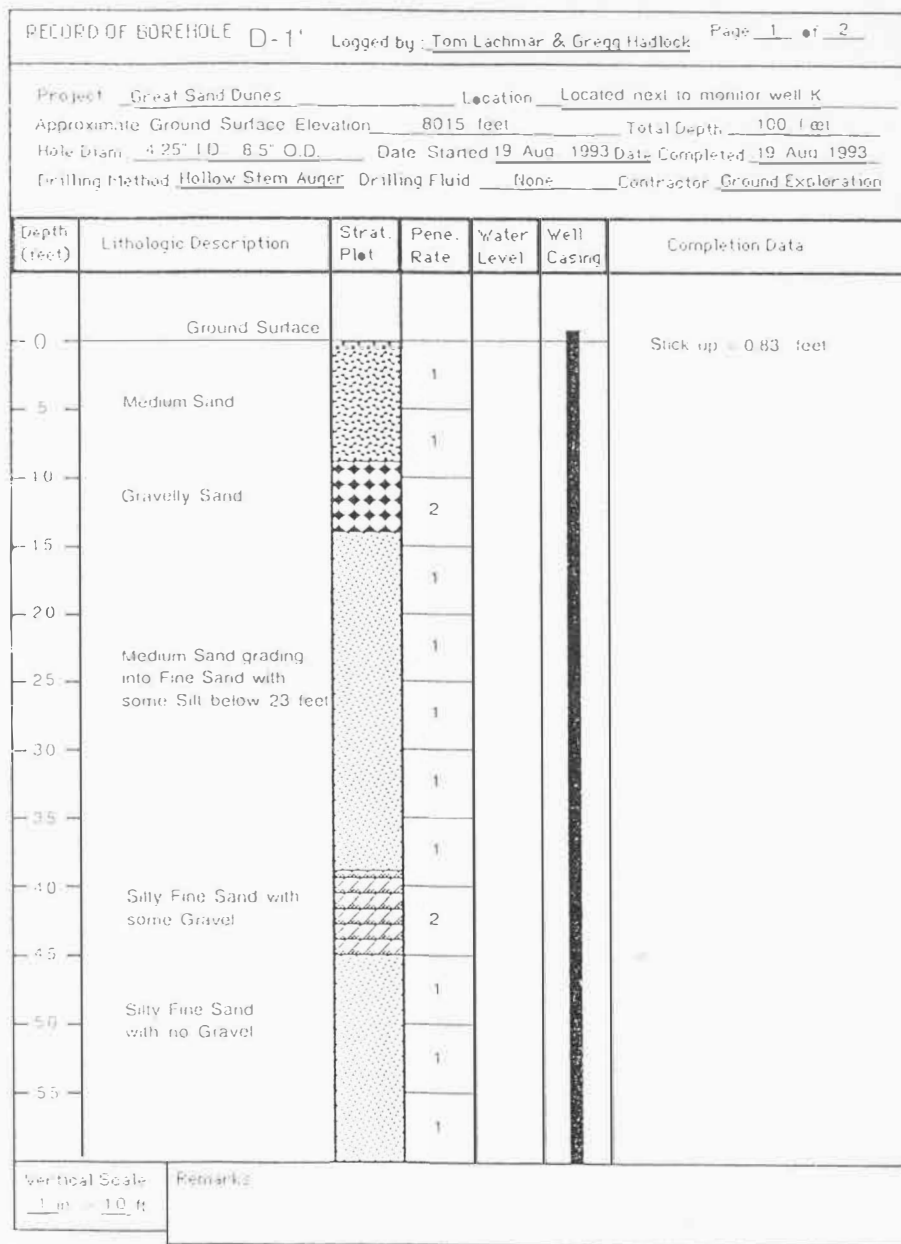


Figure 13. Record of borehole D-1' (page 1.)













RECORD OF BOREHOLE <u>D-1'</u> Logged by <u>Tom Lachmar & Gregg Hadlock</u> Page <u>2</u> of <u>2</u>									
Project: <u>Great Sand Dunes</u> Location: <u>Located next to monitor well K</u> Approximate Ground Surface Elevation: <u>8015 feet</u> Total Depth: <u>100 feet</u> Hole Diam: <u>4.25" I.D. 8.5" O.D.</u> Date Started: <u>19 Aug 1993</u> Date Completed: <u>19 Aug 1993</u> Drilling Method: <u>Hollow Stem Auger</u> Drilling Fluid: <u>None</u> Contractor: <u>Ground Exploration</u>									
Depth (feet)	Lithologic Description	Strat. Plot	Pene. Rate	Water Level	Well Casing	Completion Data			
60	Medium Sand		1	 91 feet		Aug. 19 P.M. Water Level = 91.83 feet below Top of Casing			
65			1						
70			1						
75			2						
80	Silty Fine Sand with some Gravel (Possibly interbedded)		2						
85			2						
90			2						
95			2						
100	Hard Layer (Gravelly Sand?)		4						
	Medium Sand		2						
<div style="display: flex; justify-content: space-between;"> <div style="width: 30%;"> Vertical Scale <u>1 in = 10 ft</u> </div> <div style="width: 70%;"> Remarks </div> </div>									

Figure 13. Record of borehole D-1' (page 2.)

RECORD OF BOREHOLE D-2						
Logged by: <u>Tom Lachmar & Gregg Hadlock</u> Page <u>1</u> of <u>1</u>						
Project <u>Great Sand Dunes</u> Location <u>Roughly midway between well K and well C-1</u>						
Approximate Ground Surface Elevation <u>7950 feet</u> Total Depth <u>50 feet</u>						
Hole Diam. <u>4.25" I.D. 8.5" O.D.</u> Date Started <u>18 Aug. 1993</u> Date Completed <u>18 Aug. 1993</u>						
Drilling Method <u>Hollow Stem Auger</u> Drilling Fluid <u>None</u> Contractor <u>Ground Exploration</u>						
Depth (feet)	Lithologic Description	Strat. Plot	Pene. Rate	Water Level	Well Casing	Completion Data
0	Ground Surface					
5	Medium Sand		1			
5	Gravelly Sand		6			Hit water at about 6 feet
10	Sand and Gravel		2			
15	Medium Sand with some Gravel		1			There is no casing installed in this borehole
20			1			
25			1			
30			1			
35	Grading into Medium to Fine Sand with some Silt below 25 feet		1			
40			1			
45			1			
50			1			
55						
Vertical Scale <u>1 in. = 10 ft</u>		Remarks: C-1 Total depth = 14.91 feet Water level = 11.34 feet below Top of casing (Stick up = 0.33 feet)				

Figure 14. Record of borehole D-2.